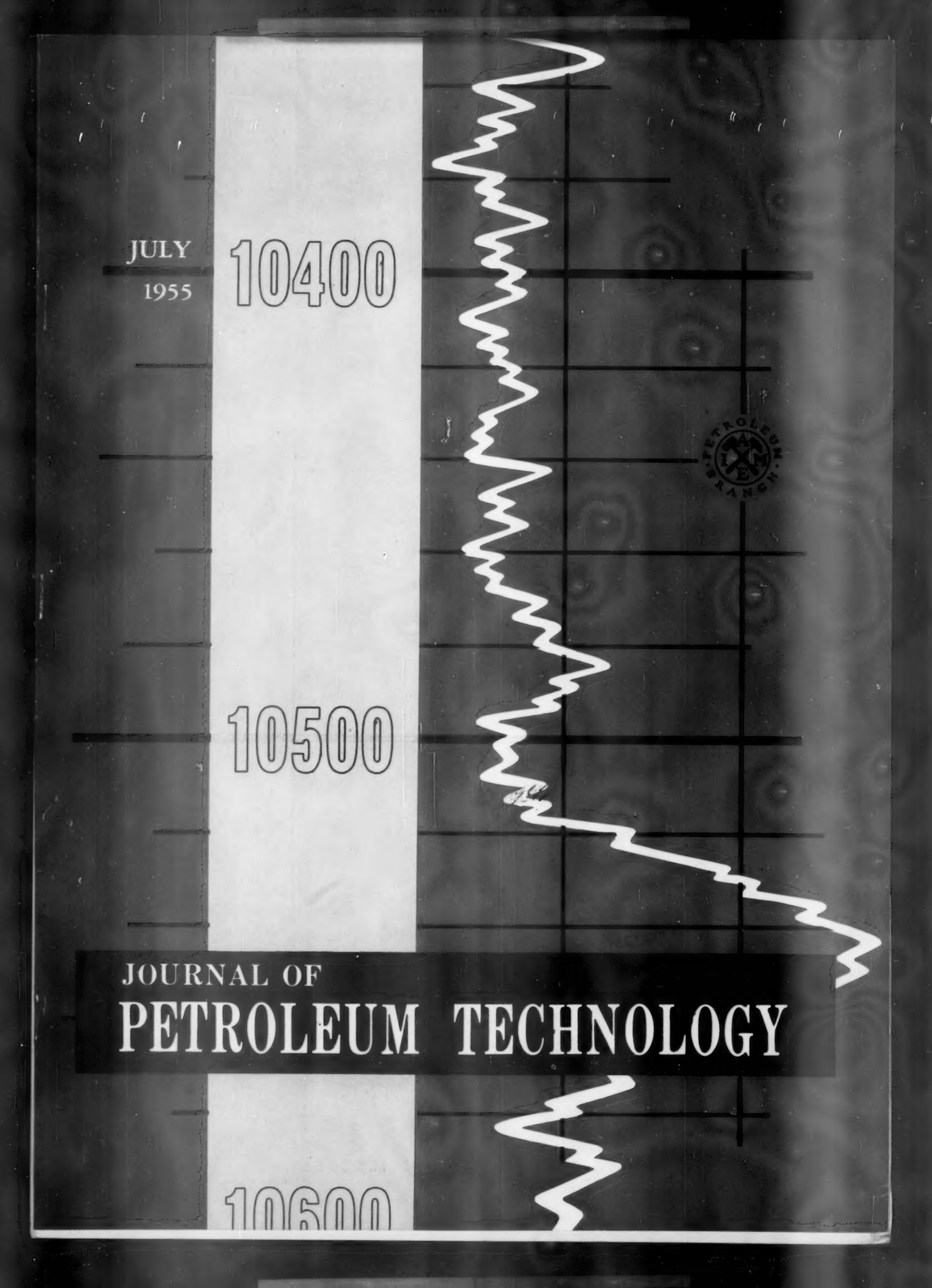
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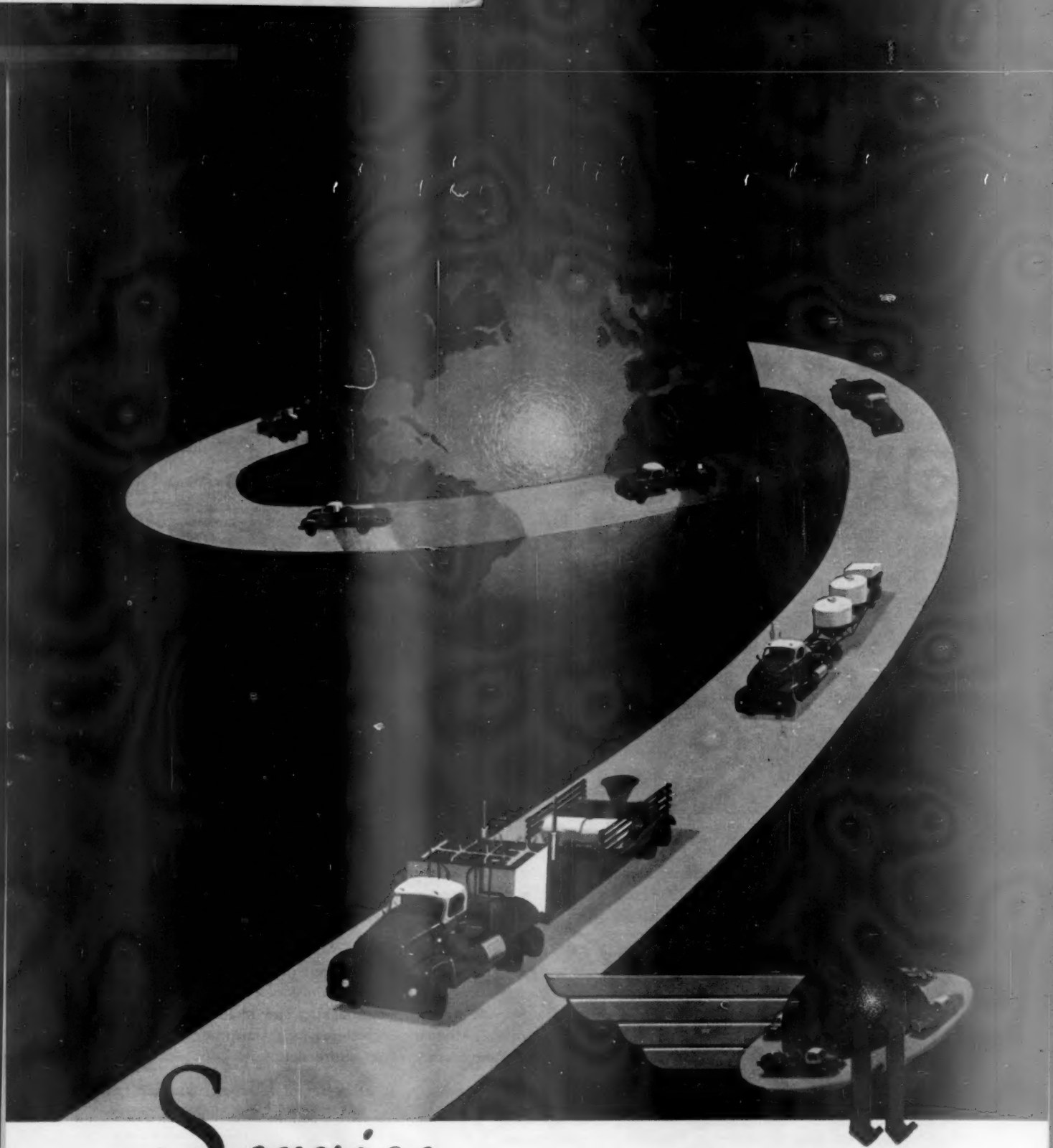

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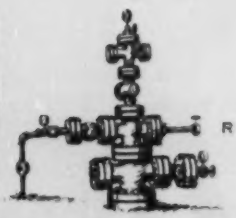

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On the Cover: Since the subject of logging is treated several times within this issue, the artist has rendered his conception of a portion of a log. A list of proposed logging symbols for the industry is published on page 31, and two papers on logging are featured in the Petroleum Transactions section.

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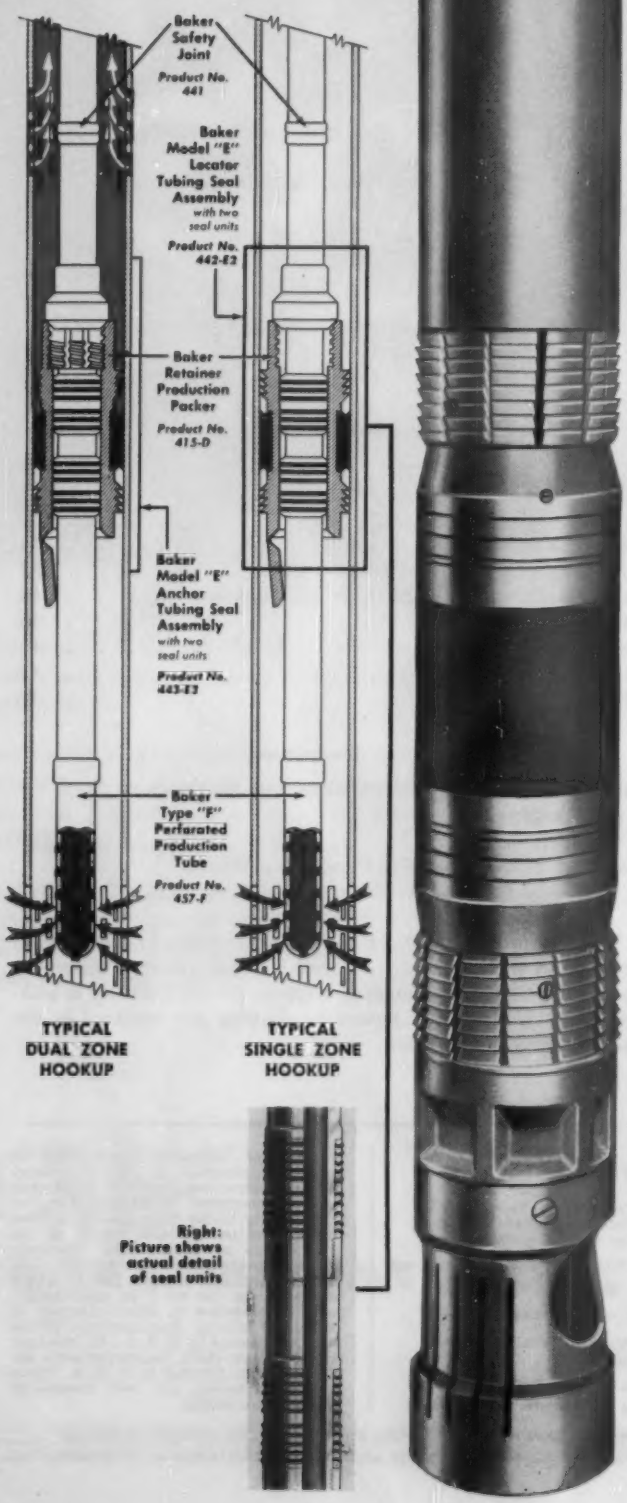
WITH 1 BAKER

RETAINER PRODUCTION PACKER


Baker Safety Joint
Product No. 441
Baker Model "E" Locator Tubing Seal Assembly with two seal units
Product No. 442-E2
Baker Retainer Production Packer
Product No. 415-D
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TYPICAL DUAL ZONE HOOKUP
TYPICAL SINGLE ZONE HOOKUP
Right: Picture shows actual detail of seal units

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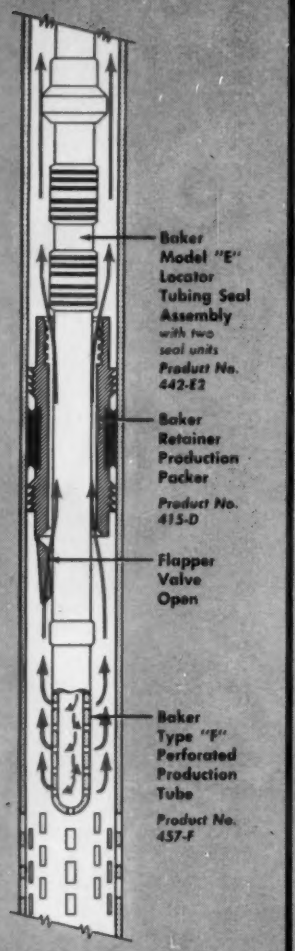
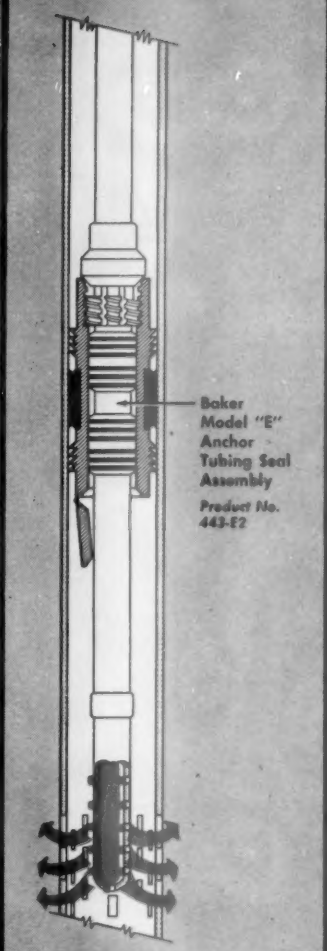
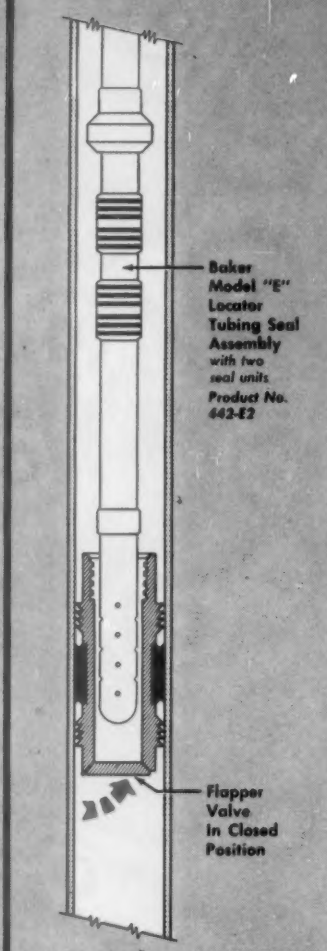

Baker Model "E" Locator Tubing Seal Assembly with two seal units Product No. 442-E2
Baker Retainer Production Packer Product No. 415-D
Flapper Valve Open
Baker Type "F" Perforated Production Tube Product No. 457-F

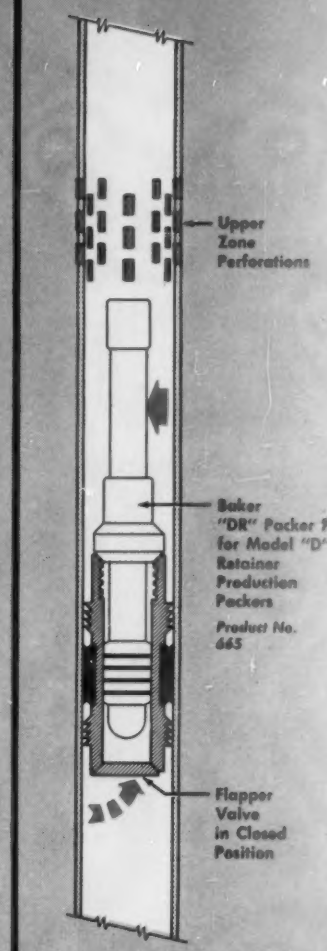
Washing or Circulating—Seals of Locator Tubing Seal Assembly removed from packer bore. Flapper Valve held open by tubing extending below the Packer.



Pressuring Below Packer—Acid or cement squeeze, formation fracture, gas or water injection. Anchor Tubing Seal Assembly is used when high squeeze pressures are required.



Isolate Zone Below Packer—Tubing String removed, Flapper Valve closed. Isolates pressure differentials (squeeze, production) from below the packer.


Upper Zone Perforations
Baker "DR" Packer Plug for Model "D" Retainer Production Packers Product No. 665
Flapper Valve in Closed Position

Temporary Bridge Plug—For working over zones above the packer. DR Plug is run in on Baker Retrievable Cementer and retrieved with overshot.

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FEATURE ARTICLE

CANADIAN OIL at the EIGHTH MILESTONE (1947-1955)

W. O. TWAITS

IMPERIAL OIL LIMITED
TORONTO, CANADA

Introduction

Recently Canada celebrated the eighth anniversary of a discovery which to Canadian oil men ranks with that made by Columbus. The finding of crude oil at Leduc, Alta., eight years ago on Feb. 13 had some other similarities with the experiences of Christopher Columbus. As with the discovery of America, the significance of finding oil in Canada was not immediately recognized. Today, at the comparatively advanced age of eight, and with an unprecedented rate of growth, there are few who are not aware of the size or importance of the Canadian development.

It seems appropriate at this time to examine some of the factors influencing the economic behavior of this new supply source—not in detail, but rather in terms of future growth.

Canadian Oil Today

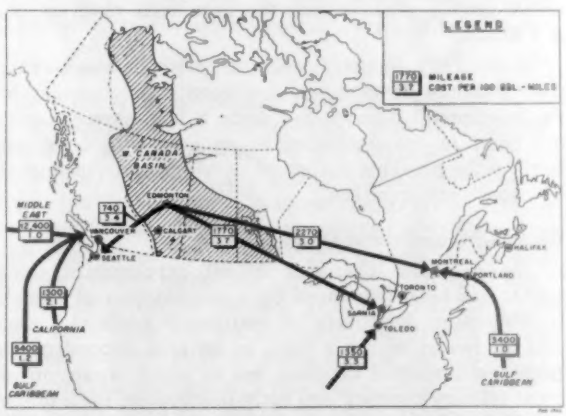
The stature of present Canadian oil can be measured with considerable ease and a minimum of statistics. Eight years of progress has brought the industry to the point where it supplies the needs of virtually all of Canada west of Toronto on Lake Ontario. This is in marked contrast with the 1947 situation in which an area near the Arctic Circle and another around Calgary were the only sections supplied with local crude.

This widening of the area supplied reflects the growth of total reserves from 72 million bbl to some 2¾ billion and of daily average production from a declining position at 20,000 to a position with excess maximum efficient recovery at 260,000 bbl. Potential production has risen to around 420,000 bbl. There are a great many other measurements of progress which could be enumerated, but the one which is perhaps most striking from a Canadian viewpoint is that current production with a 1954 gross value of $245 million effects a foreign exchange saving of considerably more than that amount. This saving of foreign currency is in U. S. dollars, and it is augmented by the inflow of additional cash for investment in oil development by companies and individuals.

This aspect is the more noteworthy because 1947 was a year of crisis for Canadian currency. Drastic controls were introduced in that year to prevent the Canadian dollar from going to an excessive discount. Today, after eight years of oil development, our chief exchange problem is to prevent the Canadian dollar from going to an excessive premium. In fact, the exchange premium is currently costing Canadian producers some 10 cents/bbl in wellhead price, which is the amount by which competitive imports are reduced in price by the exchange differential.

While it would be wrong to credit oil with being more than one factor among many in changing Canada's exchange rate, it is certain that the oil development has contributed heavily to a northward shift which has taken place in the continent's economic center of gravity. Canadian oil, together with other resource development, has helped to change continental relationships.

The continental aspect soon strikes any serious student of the development, whether from a geological, financial, industrial, economic, or strategic standpoint. From all points of view, Canadian oil has continental implications and involvements.



Prairie crude has reached markets nearly 2,000 miles from the fields, traveling over interior lines, which are high in cost relative to ocean tanker rates.

Paper presented at AIME Annual Meeting in Chicago, Feb. 13-17, 1955.

The Development

Geologically, the Western Canada Basin is a part of the central sedimentary area running from the Gulf of Mexico to the Arctic Ocean. For the most part, the Canadian development has naturally involved similar operating techniques to those used in the Mid-Continent, Rocky Mountains, and Permian Basin areas. The Canadian climate and terrain in some parts of the basin introduce complicating factors not usually experienced in the United States. In northern areas remote from settlement, the requirements of camps and special equipment have to be geared to extremes of temperature and occasionally to long periods of isolation. By and large, any additional costs involved are a function only of terrain and remoteness, rather than international boundaries.

From a financial standpoint the continental aspect is also pronounced. The Canadian development has been financed in basically similar fashion to that in the United States; that is, with risk capital furnished by earnings plowed back by the oil industry, with risk money from the investing public and mortgage money from lending institutions.

U. S. Capital

In this connection, the role that the new U. S. capital has played in the Canadian development is important and yet sometimes exaggerated. While it is not possible to state with any degree of accuracy the extent to which the Canadian oil industry has been financed by funds from the United States, in terms of book value United States investment now represents some 50 to 60 per cent of the total investment.

It is worth noting that all types of operations have been represented in this movement of capital from the major oil companies to the lease brokers. This percentage, of course, is substantial—with cumulative expenditures to date amounting to $2,600 million. But more surprising is that Canadian capital should have contributed as much as it has to the development when the small extent of crude oil resources prior to 1947 is taken into account.

Perhaps the most significant difference between the U. S. and Canadian scenes from an operational standpoint is the ownership by the provincial governments, of from 50 to, in some areas, 100 per cent of mineral rights. This means that the mineral owner's revenues, which go to enrich the landowner in U. S. oil-producing areas, largely go to enrich the provincial governments in Canada.

In ancillary industry, such as petrochemicals, etc., the Canadian development has been closely similar to the continental pattern. But since it has taken place in the heart of the continent, in an area with comparatively little previous industrial development, the impact has been very apparent.

Rate and Character of Development

The rate and character of oil development since Leduc has been influenced by a combination of factors worth noting. Discovery of two major pools at Leduc and Redwater within a year, in an area dependent on high-cost imported supplies, led to rapid expansion of local refinery capacity and early justification for a major pipeline outlet.

At the same time, lease obligations on government lands were generally designed to promote rapid evaluation in the exploration stage and rapid development after discovery. In all western provinces, regulations on government land involve work obligations and graduated rentals during the exploration phase; after discovery, leasing on a checkerboard pattern leaves proven acreage for sale by closed tender bidding to the government.

This has been and continues to be an important economic factor since the government holds mineral titles on 50 per cent to 100 per cent of acreage in Western Canada. In this atmosphere, pressures and problems that have taken many years to evolve in other areas were quickly generated. The Canadian industry has had to condense a great deal of experience into a few short years, and it was inevitable that it should borrow from the accumulated oil history of the United States. Conservation legislation and regulatory practices have been established with the full background of legal and operating experience of the Mid-Continent and Texas. Prorationing to market demand was set up in Alberta early in the conservation program.

Provincial administration has been of a very high order with full recognition given to the identity of interest between producer and mineral owner. At the same time a strong industry association has grown up to handle the manifold problems of industry and public relations which were all the more acute because of rapid development.

Advantages of Experience Abroad

One of the advantages that Canada has gained from experience abroad is that of being able at this early stage to better evaluate crude reserves and ultimate potentialities of the Canadian region. Reserves of light crude, currently estimated to be as high as 2¾ billion bbl rose by 370 million bbl in 1954, which may in time with revisions and extensions approach 600 million bbl. This is six times the year's crude production.

On the basis of exploration experience to date in U. S. sections of the continental basin, the prospective area of Canada should develop from 20 to 25 billion bbl of light crude over a normal producing generation. There are, of course, additional resources in the form of heavy crudes, oil shales, and the famous tar sands of Athabaska—the latter alone being estimated at the equivalent of 100 to 300 billion bbl.

It is not necessary to speculate on the tar sands to assess the importance of future Canadian oil prospects. The estimate for light oil of 20 to 25 billion bbl is sufficient to forecast a producing rate of several million barrels daily, and a lasting development of petroleum energy on a large scale. Of course, this is a long term viewpoint in which time is a relative term.

Markets for Canadian Oil

The current problem of Canadian oil is not connected with ultimate possibilities so much as with proximate realities. Today, Western Canada has a potential at maximum efficient recovery rates of about 420,000 B/D. Actual production for 1955 will probably average about 330,000 B/D, with closed in production of some 100,000 B/D of 30 per cent. The markets being supplied in 1955 will, it is estimated, consist of the following areas and average year's quantities:

West Coast	B/D	
British Columbia	49,000	86,000
Puget Sound	37,000	
The Canadian Prairie Provinces	118,000	
Eastern Movement		
The U. S. Lakehead-Minneapolis area	21,000	126,000
Ontario	105,000	
	330,000	

Three Successive Phases

Canadian crude has spread out to serve these markets in three successive phases. First came the prairie provinces, whose needs were satisfied by the middle of 1949 with the completion of refinery expansion programs. Then followed extension eastward to Ontario, by construction of the Interprovincial pipeline which now extends some 1,700 miles from Edmonton to Sarnia. This system has an ultimate capacity of about 300,000 B/D. The movement into Sarnia brought Canadian oil into competition with the many and varied supplies entering the Great Lakes market. With major pipeline systems from the Gulf, Mid-Continent, and Rocky Mountain areas, plus offshore supplies moving west from Montreal and the Hudson River Canal, this area represents world-wide oil competition. The price of Canadian crude accordingly has reflected, and continues to reflect, all these forces. The latest market to be added, British Columbia and the Pacific Coast, came with the completion of the Trans-Mountain pipeline in 1953.

No price reduction was required to establish this movement, since limiting competition was set in the eastern market. At present, despite low ocean tanker rates, Canadian crude is competitive in this area with all sources of supply.

In these various advances, the economic development of Canadian crude has been moulded by its peculiarly landlocked environment — a characteristic which has had an unusually marked influence on its past development and future prospects.

Offshore Imported Crudes

Reduced to somewhat over-simplified terms, the landlocked feature of Canadian crude means that it must compete at long range with offshore imported crudes. And where the orbits of most competitive crudes are conditioned by large ocean tanker transportation costs, Canada's crude must adapt itself economically to pipeline transport costs. In other words, Canadian crude must move at costs of roughly 3 cents/100 bbl miles in big inch pipeline systems. Tanker-borne crude, traveling at perhaps 1 cent/100 bbl miles can be moved well over 5,000 miles for as much as it costs to move Western Canadian crude the 1,770 miles from Edmonton, Alta., to Sarnia, Ont. In effect, Canadian crude must absorb 4 cents/100 bbl miles moving toward tidewater competition. It is also apparent that the waterborne crude has the advantage in flexibility of route as well as cost.

The comparatively rigid and high cost transportation connections through which Canada's crude must operate imply two basic economic considerations for the industry. First, Canadian crude prices will inevitably reflect a heavy transportation "penalty." Second, any decision for marketing Canadian oil, due to the relative inflexibility of the transportation system, will have very lasting effects.

A third consideration should be mentioned. Since the majority of mineral rights in Western Canada are held in trust for the people, the governments of these provinces represent the mineral owner's interest in gaining the best possible return for oil at the wellhead. This strengthens the natural objective of the producer to gain the best possible price for his oil. Added to the comparative rigidity of an industry which must operate on interior continental lines, it lends further emphasis to the industry's desire to avoid any unnecessary, though nonetheless permanent, transportation penalties.

The relative wellhead prices of comparable American crudes — translated into U. S. currency — show this transportation disadvantage as follows:

	Per Bbl
Edmonton (Redwater)	$2.58
Rocky Mountain	2.80
Mid-Continent	2.80
Gulf	2.80
California	3.21
Venezuela (f.o.b. tanker)	2.85

A Major Consideration

The figures demonstrate the price situation as it stands today and, why facing a differential of 22 cents/bbl or more, Canadian oilmen must stop to consider before risking any further detraction from the long term attractiveness of Western Canada as an area in which to look for crude oil. Canadians sometimes think of all mining and mineral production as being similar to gold, with its fixed high price which makes it profitable to search for gold in almost any part of the world. With the increasing emphasis on crude mineral production, such as oil and iron, it is becoming realized that many minerals are only valuable if they can be brought cheaply to good markets, a state of affairs which can by no means be taken for granted.

One deduction from these various considerations, is that Western Canadian crude can probably never economically supply the entire Canadian market. The shortest route of physical movement from Edmonton to Halifax would be over 3,000 miles. From Edmonton to Montreal is about 2,300 miles. Perhaps the longest overland supply route traveled by crude in the United States is from West Texas to the Great Lakes—well under 1,500 miles. Without entering into other factors, it seems that the Canadian eastern seaboard market presents a most difficult transportation hurdle. On the other hand, the distance factor which limits eastward expansion is an advantage on the west coast where alternative supplies have a much longer haul.

This consideration, taken in conjunction with our growth forecasts which indicate a daily potential of more than 1 million bbl by 1960, poses as neat a set of problems as any eight-year-old ever had to solve.

The Demand

To begin with, no rational forecast of Canadian demand indicates more than 650,000 B/D by 1960 for the nation as a whole—and of this 650,000 B/D, only 400,000 B/D is in the parts of Canada now being supplied with Western Canadian crude. If we add in the Puget Sound, already being supplied with Canadian crude, and allow for the probable growth in demand of these present marketing areas, the outlet for Canadian crude grows to 550,000 B/D by 1960—still not much more than half the potential, and there will still be some 400,000 B/D or more looking for market.

An obvious suggestion is that the pipeline should be extended to Montreal, which by 1960 should be consuming up to 200,000 B/D. This has some superficial appeal, since the economies of larger-scale pipeline transport would help to offset the wellhead price reduc-

tions necessary to compete with offshore supplies. The end result would commit western crude to compete at the end of a 75-cent haul, against the Gulf and Caribbean operating some 37 cents away from their home base. That is, Canadian crude would be committed—and committed through the inflexible medium of a pipeline—to compete with these crudes at double the transport handicap.

Protective Tariff Proposed

In a period of ample supply, reducing price is no assurance of capturing a market, but the big catch is the permanence of such price reduction and its effect on future development. The realization of this aspect has led some people to suggest imposing a protective tariff on crude entering Canada.

Now, most oilmen find tariffs, quotas, and other trade restrictions repugnant in principle, even though there seem to be exceptions which justify such practices. Only a very serious situation could justify such a move, especially by a country which has so good a record in trading practices as Canada.

Moreover, there are practical objections to such a tariff proposal. The first is that while a tariff might temporarily help to extend the market eastward, it would have the effect of limiting the competitive position of the crude in other directions. In fact, a tariff in this case could only be construed as a form of transportation subsidy.

A second objection is that gasoline is already one of the most heavily taxed commodities in Canada, far more so than in the United States. Any additional tax on this major source of energy would represent a handicap to the ability of Canadians to carry on their work economically and competitively.

Answer to the Problem

What then is the answer to the problem of future outlets for Canadian crude? If "future" is defined as some time beyond the point of accurate prediction, then the answer is exceedingly simple—the problem will disappear.

This paper has discussed the problem of 1960—the stage at which Canada's growing crude potential finds the bonds of land transportation most restricting. The paper approaches the problem of 1960 with the thinking of 1955—a year in which oil supplies are ample, and nationalistic as opposed to continental thinking tends to be tolerated.

A realistic look at the future must take into account a growth in continental oil requirements to a figure of 12 to 14 million B/D in the next 20 years. Now, no matter how pressing current problems of market outlet are, it can be agreed that the normal optimism of oil seekers will have plenty of latitude in this outlook. The long term problem really is to ensure the maximum rate of exploration effort and the maximum development of oil resources against this outlook. Within this framework, the forecasted Canadian production is not a problem but an essential.

The timing of new resources and new needs is a function of many factors which can neither be predicted nor controlled, but there is the historical record of the oil business to show that the joint forces of supply and price cannot remain out of equilibrium for any length of time. In this equilibrium, it is axiomatic that oil supplies should move to the nearest and best priced market, representing the maximum incentive to the producer and the royalty owner. Any devices which endeavor to ignore this axiom must inevitably distort or retard sound development.

The author's appraisal indicates that in the short-run outlook, the solution to successive marketing problems will probably be piecemeal. Western Canada's markets will grow city by city, and refinery by refinery, rather than by the tremendous leaps they have taken in the first eight years. What can be looked forward to is steady growth and consolidation. Possibly this is the best indication that, at the eighth milestone, Canadian oil is approaching maturity. ★★★

ADVANTAGE of a COORDINATED FORMATION EVALUATION PROGRAM

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Abstract

The importance of obtaining sufficient reliable data on reservoirs has increased in recent years as wider use is made of reservoir engineering technology. These data can be obtained at minimum cost through a coordinated formation evaluation program during the development of a reservoir. Such a program and its benefits are outlined, and the results of the application of a program in a Strawn lime field is presented in this paper.

Introduction

The growth of reservoir engineering over the past 15 years has caused a fundamental shift in the approach to the production of oil. The oil operator in the 1920's and 1930's was primarily concerned with finding a porous zone which would give up oil. He drilled with tools which were constantly improved, and gradually he learned to employ the newly developed logging devices which helped to locate the oil pays. Relatively speaking (compared with today), there were large amounts of oil to be found fairly cheaply at shallow depths. *Exactly* how much oil he found or about how long it would take to recover it was of concern to the operator, but how to determine these factors was not known at that time.

Today's outlook is different. There has been a shift from thinking about individual well behavior to thinking about the entire reservoir. The basic reservoir concepts of Schilthuis[1], Buckley and Leverett[2], and others have been tried and proved and expanded. Much was learned about reservoir theories during World War II when many reservoirs were produced at high rates without apparent damage. Today, reservoir engineering has progressed so that the behavior of a reservoir can be predicted with reasonable accuracy.

The reliability of reservoir performance predictions depends upon the accuracy of the reservoir data. As new oil reservoirs are found at deeper depths and are more costly to develop, accurate recovery predictions grow more important so that a proper evaluation of risks can be made. Today also finds a new and growing need for reliable recovery predictions to establish the feasibility of unitized operations.

Every prudent operator attempts to secure all the information he can about his reservoir, often through some systematic program. That some operators get very little information and that others amass huge amounts of data (at a huge cost) is widely recognized. Many operators, large and small, have found it hard to strike a balance between necessary and superfluous data, regardless of cost. This paper presents a program, and factors to consider in implementing such a program, which can be used as a guide for obtaining adequate, reliable reservoir data.

Advantage and Benefits of a Coordinated Formation Evaluation Program

The advantage of a coordinated formation evaluation program is that sufficient data on the reservoir rock are obtained, in usable form at the time needed, at reasonable cost. Having adequate data available is of extreme importance at the time recovery calculations are started and when equities are determined for unitized participation. Usually, drilling is substantially complete at those times, and such data may be unavailable unless a coordinated formation evaluation program has been employed. In many instances, lack of coordination in obtaining data results in additional drilling and other expensive procedures to secure adequate information.

Benefits from a successful formation evaluation program accrue at many stages during the producing life of the reservoir. First, and most attractive to the operator at the time the program is started, is the establishment of a sound reservoir basis for well completions. The operator thus gains through standardized optimum completion procedures which minimize future workovers to secure proper reservoir drainage.

The greatest benefit derived from a coordinated formation evaluation program is the supply of reliable data on the reservoir rock, which, when used with data on the reservoir fluids, permit reasonably accurate determination of recovery from the reservoir. This allows early appraisal of the merits of pressure maintenance

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or secondary recovery after primary depletion, which may result in additional hydrocarbon recovery.

Benefits from a coordinated formation evaluation program may also be gained when unit operation of a reservoir is considered. In Texas, Senate Bill 24[3] (1949) provides that operators may join together in unit operation in order to prevent waste. The apportionment of interest in a unit can be made more easily and fairly on each operator's properties when a complete set of data is available. Without such data, some units have been forestalled indefinitely, and in others some operators have been forced to spend large sums to establish their equities. The program outlined in this paper is designed to avoid such problems.

Adequate knowledge of the properties of the reservoir rock is also beneficial during depletion of the reservoir. In competitive operations, reservoir engineers can predict fluid migration, which will enable the operator to take corrective measures to maintain his participation in production. Formation evaluation data are necessary to check reservoir performance at various stages of depletion so that maximum recovery is obtained. Furthermore, a realistic analysis of problem wells can be made only when adequate reservoir data are available.

Sources of Formation Evaluation Data

The basic data necessary to evaluate oil and gas reservoirs consist primarily of the following: (a) net reservoir oil and gas zone thicknesses, (b) productive limits, (c) porosity, (d) interstitial water saturations, (e) residual hydrocarbon saturations, and (f) reservoir conformance data. These data, together with the data on the properties of the fluid in the reservoir, enable the reservoir engineer to make predictions describing future performance and to evaluate various producing plans available to the operator. The reliability of the reservoir engineer's analyses is dependent upon the quality of the data which are available to him.

Formation evaluation data are generally obtained from core analyses, well logs, and formation tests. The coordinated formation evaluation program is essentially the employment of the three basic data sources so that the information from each complements the information from the others. No single method of obtaining formation evaluation information is adequate to give all the data necessary. Core analyses come closest to giving all the desired information; they are also the only means by which some of the information can be obtained. The coordinated program, therefore, includes a well-planned program of coring and core analysis supplemented by well logging and formation testing.

Coring and Core Analysis

A great amount of effort has been put into refining techniques of obtaining cores and into developing methods of learning their secrets. The use of diamond coring equipment and developments in conventional core-cutting methods[4] have made it possible to obtain fairly reliable samples of adequate size of almost any reservoir rock.

Technological developments in reservoir engineering have created a need for more accurate core analysis data and also for new measurements that have not been made in the past. On a routine core analysis, most laboratories measure porosity, absolute permeability, and core fluid saturations. In addition to the data normally determined, the reservoir engineer needs data describing the fluid distribution in the reservoir, the residual oil saturation after water flooding, the relative permeability relationships, and in some instances the electrical properties of the rock. In order to make these measurements accurately, cores of sufficient size should be taken from the reservoir. In sandstone reservoirs, cores about 3 in. in diameter are required so that plugs 1 in. in diameter and 2 in long may be cut parallel to the formation bedding planes. Large-core analysis is generally used on fractured or vugular formations, and the core size needed for this analysis is from 3 to 5 in. in diameter and 8 to 12 in long.

Analytical techniques now available require cores of sufficient size which have been handled properly to provide accurate data on the core properties. The handling of the cores prior to the analysis is as important as the analytical techniques used by the laboratory when reliable data are to be obtained.[5] The coordinated formation evaluation program should be planned so that the core properties to be measured are not destroyed before the core reaches the laboratory.

Well Logging

The realization that more and better basic reservoir information is needed, and that some of the data can be obtained at lower costs through log interpretation, has resulted in development of new well logging techniques and improved methods of interpreting logs obtained by older methods. Certain quantitative log interpretation methods are now accepted by the industry. Data on porosity, interstitial water saturation, and reservoir thickness usually can be obtained when the proper logs are run and proper interpretation techniques are utilized.

There are many different types of well logs, any one of which may provide valuable formation evaluation data. The coordinated formation evaluation program provides for determining the logging methods that will yield the most information, and these logging methods should be used in the wells drilled to the reservoir.

Testing

The third data source is the principal means of defining the productive limits: formation testing. A number of important improvements in testing techniques and tools have become available in the past few years, and these improved methods should be used wherever possible. It is important that drill-stem tests provide as accurately as possible a measure of the capacity and fluid content of the zone tested.

A Coordinated Formation Evaluation Program

The ideal time to obtain the data required to evaluate a subsurface oil or gas reservoir is during the development of the reservoir. The coring programs and virtually all of the logging must be done when the wells are drilled. This is the time when the data can be obtained at a minimum expense. This is also the time when the reservoir engineer should see to it that the data he will need are obtained so that he can cope with the various problems that will arise during the development and depletion of the reservoir. A coordinated formation evaluation program should therefore be planned shortly after the discovery well in a reservoir is drilled.

A program which has been found to provide adequate data at a minimum expense as new reservoirs are developed consists of the following principal elements:

1. Key wells are selected at uniform intervals to provide representative coverage over the reservoir. These wells are then: (a) cored through the entire reservoir section, and (b) logged with various logs which have quantitative interpretation applications.

2. Complete core analyses are obtained on cores of key wells for: (a) porosity, (b) permeability, (c) interstitial water saturations, (d) residual hydrocarbon saturations, (e) capillary properties, (f) relative permeability to reservoir fluids, and (g) electrical properties.

3. The logging method which provides the most reliable quantitative and other information (determined by key well data) is applied in non-key wells. Ordinarily, this will require similar well completions to the key wells. Such a program permits direct comparison of logs of all wells.

4. Wells which penetrate gas-oil and oil-water contacts are tested to determine those contacts as nearly as possible. Log interpretation of contacts should be utilized wherever possible to minimize the testing required.

5. A continuous search is maintained for improved techniques and procedures, and a careful check is kept on the quality of the program in progress.

While the above program is tailored for development of a new reservoir, parts of it may be adapted to old reservoirs where little or no formation evaluation data are available. Only a small amount of data is available on many prolific reservoirs which were drilled before the advent of accurate well logging and core analysis methods. In many instances, it is possible to obtain much-needed basic information on these reservoirs with the tools now available. For example, in one large Gulf Coast field, a coordinated program has been employed to obtain data from wells drilled 20 years ago, so that reservoir performance can be studied and maximum recovery assured. A coordinated formation evaluation program in this type reservoir has important benefits, which in some instances may equal those from such a program in a new reservoir.

Suggestions in Applying a Coordinated Formation Evaluation Program

The application of a coordinated formation evaluation program in a new reservoir involves all phases of reservoir development. The planning and adoption of the program should be accomplished as soon after the discovery of the reservoir as possible, since the program should result in significant savings in developing the reservoir. It must be realized that each reservoir presents different problems, and no specific rules can be set out that will cover all cases. However, listed below are a number of recommendations which have been found useful in putting a program like the one described above into operation:

1. Select key wells so that information is obtained on the entire reservoir, both areally and vertically.

2. Choose a coring method that will give as much core recovery as possible.

3. Obtain cores that are large enough for accurate core analysis.

4. Protect the cores so that the desired properties to be determined are not destroyed before the core reaches the laboratory.

5. Consider the uses of the core analysis data when determining what analysis procedures to use and what data are desired.

6. Determine the electrical properties of the drilling fluid, both mud cake and mud filtrate, to aid in quantitative log interpretation.

7. Use the same type drilling fluid and the same hole size in all wells. The program in key wells must be the same as other wells so that data can be readily extrapolated.

8. Have the logs recorded on scales large enough to be read accurately.

9. Utilize the logging methods most applicable to the reservoir based on logging conditions such as mud resistivity, formation resistivity, bed thickness, and mud filtrate invasion.

10. When formation tests indicate water, select adequate samples to determine the source of the water.

11. Obtain an analysis of formation water.

12. Establish a standard of accuracy for each element in the program and diligently maintain that standard.

The Coordinated Formation Evaluation Program in a Strawn Lime Field

Description of the Reservoir

The Strawn lime oil reservoir and its adjoining gas cap are about 9 miles long, 6 miles wide, and underlie about 18,000 acres. The reservoir is found at a depth of about 5,400 ft and averages 43 ft in thickness. Loss of porosity bounds the reservoir on the updip (east) side of the gently sloping monocline structure, and salt water bounds the oil on the downdip side. The

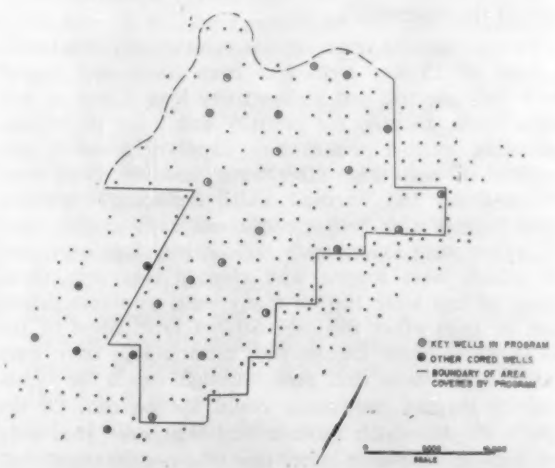

Fig. 1 — Map of cored wells in the Strawn lime field.

porosity is primarily intercrystalline with some vugs and slight fracturing; effective porosity averages about 5 per cent.

Cumulative production from June, 1949, the reservoir discovery date, to Sept., 1954, totals 13.2 million bbl. Development of the reservoir is considered complete; 11 operators drilled and completed 312 oil wells, 2 dry holes later converted to gas-injection wells, and 3 gas wells in the reservoir. A peripheral gas-injection pressure maintenance program has been in operation since March, 1953. All produced gas is gathered and liquids are extracted in a gasoline plant before the residue (about 80 per cent of the produced gas) is returned to the reservoir through systems which connect to 13 gas-injection wells. Initial work has been completed on two pilot water floods to supplement the gas-injection program.

The Formation Evaluation Program

An extensive formation evaluation program was developed for the Strawn lime field when it became apparent that the reservoir was one of major proportions. The importance of making reservoir studies to evaluate economics of development and operation was recognized soon after the discovery, and plans were made to obtain the necessary data.

The program consisted of the coordinated use of coring and logging for obtaining reservoir data. The essential elements of the program were:

1. A group of key wells was selected to provide representative data on the entire reservoir. Each key well was to be: (a) cored, (b) logged with radioactivity (gamma ray and neutron) logs, (c) logged with electric log and contact-type log, and (d) completed in one of two standard well completions.

2. A well completion program was established for non-key wells to be completed in one of the two standard well completions: (a) 4¾-in open hole below 5½-in casing or (b) through perforations in 5½-in casing.

3. A logging program was developed providing for radioactivity logging of all wells. (Originally only key wells were to be electric-logged.)

4. Cores of key wells were analyzed by large-section core analysis procedures.

Testing was not an integral part of the program; but as development progressed, a series of tests was made to determine the oil-water contact in the north part of the reservoir.

By the time the reservoir was substantially developed, a total of 19 key wells had been cored and logged with both electric and radioactivity logs. Cores of key wells were analyzed for porosity and other properties, including relative permeability, capillary pressure, and residual oil saturation after water flooding. Logs were obtained on 165 uncored wells, including 85 which were logged with both electric and radioactivity logs, 52 which were logged with radioactivity logs only, and 28 which were logged with electric logs only. Both types of logs were run on many wells to obtain definition of beds other than the Strawn lime. Most of the wells which were logged with electric logs only were cased with 4½-in drill pipe, through which the radioactivity logging instrument could not be run. Of the 156 wells in which radioactivity logs were run, only 15 were in hole sizes other than the two standard well completions.

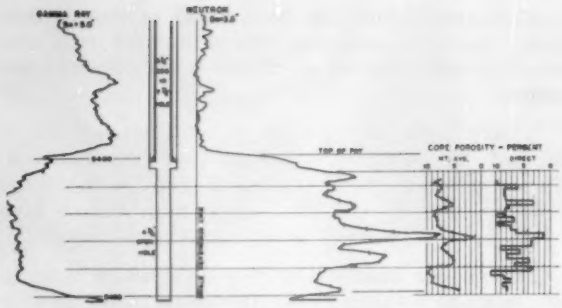

Fig. 2 — Typical correlation of core porosity and neutron log deflection, Strawn lime field.

Results of the Program in the Strawn Lime Field

The coordinated formation evaluation program provided a large amount of data on the Strawn lime reservoir. Porosity data were obtained from cores of key wells and from neutron logs[6] of other wells. Permeability data were available from cores of key wells, and permeable zones were indicated by contact-type logs[7] of many wells. The oil-water contact in the north part of the reservoir was determined by drill stem tests.

The formation evaluation data, together with data on two reservoir oil samples, permitted reasonably accurate determinations of the following:

1. Recovery by primary depletion (dissolved gas drive).

2. Recovery by pressure maintenance with (a) dispersed gas injection, (b) peripheral gas injection, and (c) peripheral gas injection and water flooding.

3. Economics of operation under the various methods of recovery.

4. Efficiency of gas injection and waterflood programs.

5. Analyses of problem well behavior.

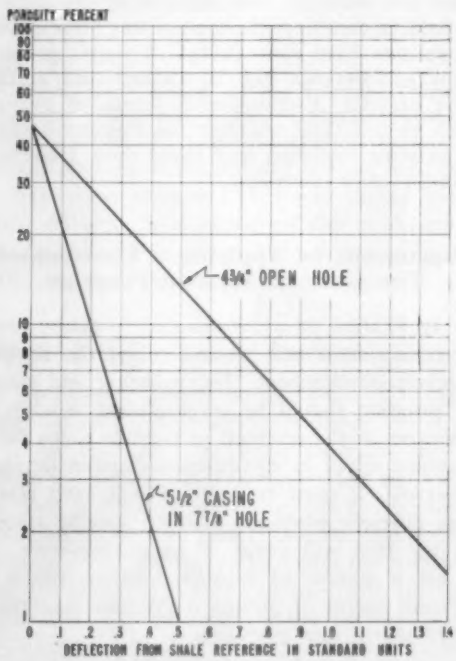

Fig. 3 — Neutron log calibration curves, Strawn lime field.

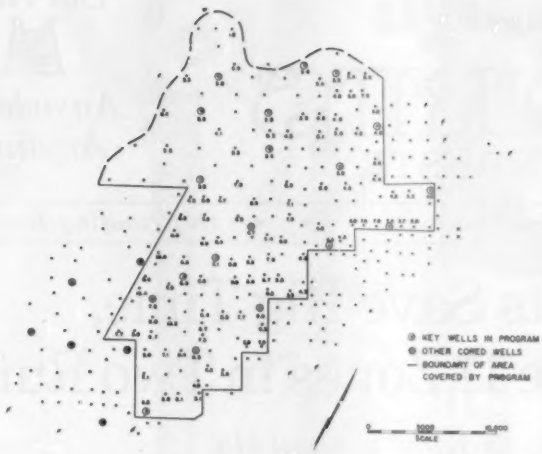

Fig. 4 — Porosity map based on core and neutron log data, Strawn lime field.

Reliable data for accurate calculation of recovery by various methods were essential to determining the need for pressure maintenance. Since completion of initial reservoir studies and the start of gas injection, the reservoir data have been used to evaluate the pressure maintenance program and to make estimates of performance with supplemental water flooding. In addition, problem well behavior is analyzed and workover remedies are planned accordingly. Benefits from adequate reservoir data will endure to depletion of the reservoir.

Considerable savings resulted from the coordinated formation evaluation program. Most important, but difficult to assess accurately, are the savings derived from sufficient data being available early enough that reliable calculations could be made to appraise various recovery mechanisms. A direct saving of 52 electric logs was made in wells which were radioactivity-logged only; additional log savings could have been made but for other requirements.

The data on the Strawn lime reservoir are impressive in amount and comprehensiveness. However, a pioneering program on such a scale cannot be employed without difficulties and without learning lessons for future programs. The coordinated formation evaluation program presented in this paper is largely derived from experience gained in this Strawn lime field. The most difficult factor in applying the program in that field was the attainment and maintenance of a consistent standard of accuracy in all phases of the program. As techniques improve and other such programs are employed, it is anticipated that the importance of accuracy will be more widely recognized, and obtaining a reasonable standard of accuracy will not be as difficult.

TABLE 1 — CORE-NEUTRON LOG CORRELATION

4¾-in Open Hole Below 5½-in Casing in 7⅞-in Hole
Strawn Lime Field

Sensitivity = 3/5-in
Maximum Deflection = 4.43-in

	Deflection from Shale Reference Line		Porosity		
Log Depth-Feet	Inches	Std. Units*	Core (Direct) Per cent	Neutron Per cent	(Wt. Avg.) Per cent
5,407.0-08.5	2.43	.694	9.7	8.3	8.4
-10.0	2.51	.717	6.0	7.9	7.5
-11.5	2.40	.686	8.3	8.5	7.8
-13.0	2.40	.686	8.4	8.5	8.3
-14.5	2.60	.743	8.2	7.4	7.0
-16.0	2.85	.814	3.2	6.2	5.6
-17.5	2.85	.814	7.7	6.2	6.8
-19.0	2.55	.729	8.4	7.6	8.6
-20.5	2.55	.729	9.7	7.6	8.6
-22.0	2.62	.748	6.7	7.3	8.1
-23.5	2.70	.771	9.4	6.9	8.2
-25.0	3.10	.885	7.2	5.2	7.5
-26.5	3.60	1.029	6.4	3.7	5.3
-28.0	4.38	1.250	1.1	2.1	3.0
5,432.0-33.5	3.80	1.086	3.4	3.2	5.3
-35.0	2.70	.771	9.1	6.9	6.8
-36.5	2.65	.757	5.6	7.1	7.1
-38.0	3.15	.900	7.9	5.0	6.3
-39.5	3.40	.971	3.8	4.2	5.5
-41.0	3.33	.951	6.6	4.4	5.1
-42.5	2.80	.800	3.5	6.4	6.1
-44.0	2.35	.671	10.8	8.8	8.4
-45.5	2.25	.643	8.5	9.4	8.8
-47.0	2.20	.629	7.5	9.8	8.0
-48.5	2.20	.629	8.5	9.8	8.1
-50.0	2.45	.700	8.0	8.2	6.7
-51.5	2.60	.743	2.2	7.4	4.1
		Total	185.8	184.0	187.0
		Average	6.9	6.8	6.9

*Standard Units = Inches / Sensitivity

Conclusions

A coordinated formation evaluation program has been found practical in developing new reservoirs and for obtaining data on old reservoirs where little or no data exist. The advantage of such a program is that sufficient data are obtained, in usable form at the time needed, at reasonable cost. Principal benefits from this type program are gained by accumulation of reliable data which permits:

1. Establishment of a sound reservoir basis for well completions.
2. A more accurate determination of recoveries.
3. A further aid in the determination of equities where unitization can be beneficial.
4. Calculation of participation in production during competitive operation.
5. Evaluation of reservoir performance at various stages of depletion to insure maximum recovery.
6. Realistic analyses of problem well behavior.

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Three strings of casing, 5", 7" and 8⅝", cemented in steel drum and perforated by (left to right) McCullough Super Formation, Standard Casing and Super Casing Glass Jets. Standard Casing Glass Jet penetrated all three strings of casing and 7" into cement, while the other types penetrated through everything, including the outside drum.

through multiple strings of casing, extra thick cement sheaths and far into hard and extra hard formations. Holes are larger, more uniformly round and are straight sided almost the entire depth of penetration. Slugs or carrots are eliminated. These advantages mean more exposed formation area, greater production, more oil!

Single trip, multiple zone perforating jobs are commonplace. Strip Carriers may be loaded full length or sections may be left blank to leave unperforated areas in the casing. Result: Less rig time; greater efficiency; more economy!

Glass Jets Save Rig Time, Perforate 11 Zones in Two Runs

Only Three Hours Required to Shoot 618 McCullough Glass Jets in 169 Feet of Split Zones

McCullough 3⅜" Standard Casing Glass Jet Perforators with Steel Strip Carriers turned in a record time-saving performance in a West Central Texas oil well, according to a recent field report.

The well had first been logged to 6347' by the McCullough Radiation Well Logger obtaining Gamma Ray, Neutron and casing collar log. 11 thin zones were selected for perforating and for accurate measurements the zones were shot by the combination radiation-collar log depths.

618 Glass Jets, six per foot, were fired through 5½" O.D. 17 lb. cemented casing in the 11 selected zones between 6118' and 6290'. Only two runs in the hole were made.

On the first run an 87' Steel Strip Carrier was used. 294 Glass Jets were fired in five zones varying in thickness from 6' to 16'. On the second run an 82' Steel Strip Carrier loaded with 324 Glass Jets perforated six zones from 3' to 24' in thickness. In both runs the Steel Strip Carriers were blanked off between the different zones. After firing both Steel Strip Carriers were recovered intact.

Only three hours were required to complete the job, including rigging up and tearing down time.

Rig time is expensive and when a perforating job can be completed with an average of better than 200 shots per hour, the saving to the operator is considerable.

One of the most important advantages of completing a well with McCullough services is illustrated by this job. That is the extreme accuracy with which the McCullough Radiation Well Logger picked and defined the boundaries of the 11 thin zones. Thus, enabling "pin point" perforating exactly where desired without wasted time and in only two runs in the hole.

AVERAGE PENETRATION OBTAINED BY McCULLOUGH GLASS JET PERFORATORS

TYPE GUN	IN SOLID STEEL TARGET	IN ONE STRING AND CEMENT TARGET	IN TWO STRING AND CEMENT TARGET	IN THREE STRING AND CEMENT TARGET
Standard Casing Glass Jet	3¾"	7⅛"	6 13/16"	6⅛"
Super Casing Glass Jet	4¾"	8½"	8⅛"	7 5/16"
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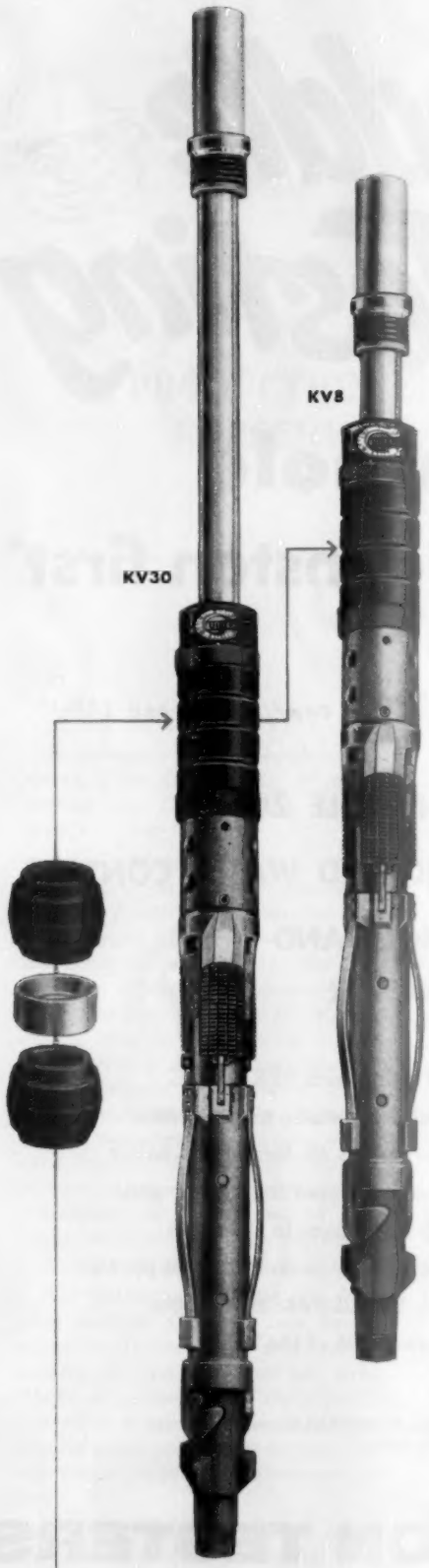

Two-piece G2 rubbers with metal spacer are interchangeable and optional at no extra cost. One-piece sleeve rubber shown on packers furnished unless otherwise specified.

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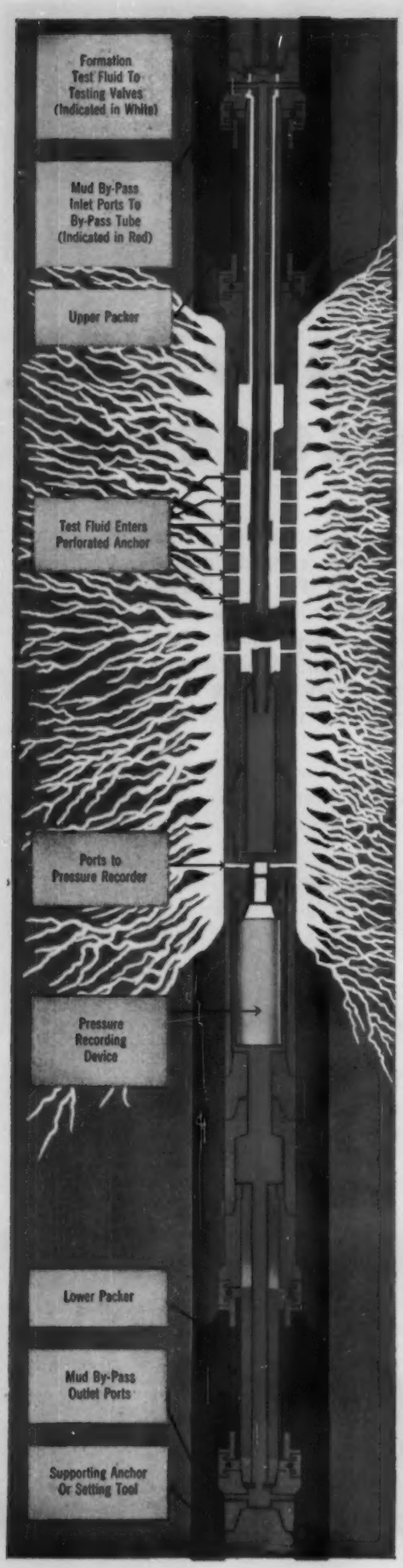
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FIELD CASE HISTORY

PRODUCTION ENGINEERING ASPECTS of SHANNON RESERVOIR, COLE CREEK FIELD, WYOMING

C. F. GATES, MEMBER AIME — GENERAL PETROLEUM CORP., LOS ANGELES, CALIF.

G. G. BROWN, JUNIOR MEMBER AIME — MOBIL PRODUCING CO., BILLINGS, MONT.

Abstract

Performance of the Shannon Reservoir, Cole Creek field, Wyo., is summarized. Oil has been secured largely by water drive.

Calculated pressure-rate performance based on Hurst's water-drive equation for an infinite reservoir coincides with observed performance. An empirical relationship indicates that the difference in pressure between the perimeter and the oil producing area for a given oil rate by water drive is about proportional to the cumulative oil produced. Calculated future performance, based on Hurst's equation, the pressure difference relationship, and the reservoir oil rate equation, correctly indicated limitations on maximum oil rate which were not apparent before the calculations were made.

Net formation withdrawals have been reduced to about zero by the injection of water in six wells spaced around the perimeter of the field. About three-fourths of the injected water rate merely replaces the former natural water encroachment rate; the remainder supports an increased oil rate.

Productivity indexes are being maintained at a maximum by keeping producing pressures at a high per cent of the bubble-point pressure through the use of "bubble-point pumps" and shut-in casingheads. The maximum efficient rate of the reservoir is automatically produced thereby. Productivity indexes of wells were increased many-fold by shooting with nitroglycerin.

Indicated recovery efficiency is about 33 per cent but ultimately may be higher.

Manuscript received in Petroleum Branch office on Sept. 7, 1954. Paper presented at Pacific Petroleum Chapter Fall Meeting in Los Angeles, Oct. 7-8, 1954.

Introduction

Although the Cole Creek Shannon reservoir is relatively small, it is of especial interest to the production engineer for the following reasons:

1. Reasonably complete field data have been secured throughout the 14-year life of the reservoir.
2. The limited natural water drive is being supplemented by water injection.
3. Present installations automatically produce the maximum efficient rate.
4. The reservoir has behaved largely according to engineering calculations.
5. There are enough diverse aspects of the reservoir history to warrant intense study.

This paper consists mostly of data and our interpretations of the data. For continuity and completeness the paper repeats some data given by Whitaker and Hoenshell.[1]

Location and Development

Cole Creek field is in the southwestern portion of the Powder River Basin, about 20 miles northeast of Casper. The field is unitized.

The first Shannon zone producer, 1-21, was completed in April, 1940, pumping 430 BOPD. Drilling on 40 acre spacing continued through 1945. After the water table was defined, the remaining edge locations were left undrilled. All 32 of the productive wells were completed on the pump. At present there are 25 oil productive wells and six water injection wells.

Generally about 4,500 ft of 5½ in casing was set at the top of the sand, a 4¾ in hole was drilled through the sand, and the well was completed "barefoot."

Structure

The Shannon reservoir is a low relief, eliptical structure, as seen on Fig. 1. The highest point of the producing zone is at 1,120 ft above sea level, and the original water table was 970 ft above sea level. Although the sand thicknesses are shown on

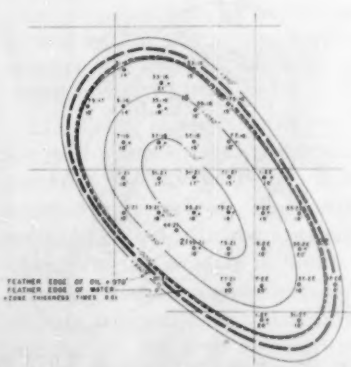

Fig. 1—Effective oil sand thickness.

Fig. 1, no attempt has been made to draw isopachous lines because of the uniform thickness. The average thickness is 17½ ft. The original area of the reservoir was about 1,600 acres.

Sand Characteristics

The sand is Upper Cretaceous, well consolidated, fine to medium grained, glauconitic, having thin shale partings and inclusions. Core analysis data are tabulated below:

Number of wells cored	19
Number of samples	291
Porosity, arithmetic average	18.7 per cent
Permeability to air	
Arithmetic average	51 md
Geometric mean	32 md
Permeability to reservoir water	
Per cent of air permeability	66 per cent
Interstitial water by capillary method	
Average	35 per cent

Fluid Characteristics

The gravity of the oil is 36 to 37° API. The bubble point was about 750 psi at reservoir temperature of 123° F. Initial solution GOR was about 120 cu ft/bbl, and initial formation volume factor was 1.075. Estimated oil viscosity under initial reservoir conditions was 3.5 cp.

Pressure Data

Estimated original pressure at datum of 1,075 ft above sea level was about 1,700 psi, or approximately 950 psi above the bubble point. Figs. 2 to 5 show development and pressures.

Pressures as of May 25, 1943, are shown on Fig. 2. The pressure in the center of the reservoir is approximately at the bubble point. Cole Creek 53-21 was completed 20 days prior to the date of the map. Its initial pressure of 750 psi is 950 psi below the initial pressure in the reservoir and is consistent with the isobaric map.

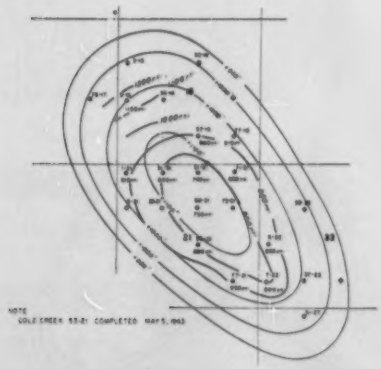

Fig. 2 — Static pressure at 1,075 ft ASL as of May 25, 1943.

During June, 1945, 37-21 was completed for water injection. As of Aug. 10, 1945, the date of pressure map in Fig. 3, 37-21 was standing awaiting installation of water-treating equipment. Even without injection, pressure in this well was 1,445 psi, or 625 psi above that of the closest producing well. The isobars are closely spaced to the west and north. Note that 33-16 was completed only about two months before the date of this map, and its pressure is consistent with the isobars.

Pressures as of Aug. 1, 1950, are shown on Fig. 4. At this time water was being injected into 37-21; its observed static pressure was 1,730 psi, or slightly higher than the original pressure of the reservoir. It should be noted that part of the reservoir is somewhat below the bubble point of 750 psi.

Pressures as of Aug. 1, 1950 are shown on Fig. 5. As of this date, two other wells, 53-16 and 75-17, had been added to the injection system. Effects of injection into these wells are shown by the configuration of the isobars.

From pressure maps, two average pressures were determined: (1) the average perimeter pressure at the original productive limit, and (2) the average pressure of the oil producing area, within the 5 per cent cut line (see Fig. 6). Of particular interest on Fig. 6 is the fact that water has encroached faster from the west and the north than from the east and the south. Because the pressure gradients were higher and water encroachment was faster, it is concluded that the water drive from the west and north is stronger than that from the east and south.

Production and Pressure Behavior

The production and pressure behavior of the Shannon zone are summarized on Fig. 7. During the first three years, pressures were above the bubble point. Because the expansibility of oil above the bubble point is low, water drive is indicated by the fact that pressures did not decline extremely rapidly. Presence of a water drive was also indicated by pressures in the center lower than those at the edges. In 1942, E. V. Watts calculated perimeter pressures from the water encroachment rates and observed performance then available, using Hurst's[2,3] water-drive equation for an infinite aquifer. Perimeter pressures calculated without essential modification of the equation have coincided with the observed data for the entire history of the reservoir. The early calculations indicated that the withdrawal rate would have to be restricted to maintain pressure. To preserve well productivity, it was believed that producing pressures should not be far below the bubble point. Despite the completion of some new wells, the oil rate was

Fig. 3 — Static pressure at 1,075 ft ASL as of Aug. 10, 1945.

Fig. 4 — Static pressure at 1,075 ft ASL as of March 1, 1948.

Fig. 5 — Static pressure at 1,075 ft ASL as of Aug. 1, 1950.

reduced gradually beginning in mid 1943; and the rapid pressure decline was arrested.

During Feb., 1946, water injection was started in one well, 37-21, at a rate of about 250 B/D. The pool oil rate was maintained at about 800 B/D, and perimeter pressure increased slightly. For 37-21 only 30 per cent of the injection rate was considered effective in reducing the net water encroachment rate.

In the early part of 1948 it was decided to increase the oil rate of the reservoir substantially and to observe performance to determine if the existing rate was the *maximum* efficient rate. The gas-oil ratio of one well, 57-16, is plotted on Fig. 7 to indicate the type of performance experienced in many of the wells. Note that the gas-oil ratio increased from approximately the original solution ratio to over two times the solution ratio, but dropped to about the original solution ratio when the rate was decreased.

Four events during the high oil rate period are of special importance:

1. Gas-oil ratios of individual wells increased substantially.

2. The average pressure of the oil producing area dropped below the bubble point.

3. The oil rate declined rapidly from 1,140 B/D in the third quarter of 1948 to 1,030 B/D in the first quarter of 1949 because of natural causes rather than as a result of manipulations by the operator.

4. No change in the observed average perimeter pressure occurred.

These events led to the conclusion that all of the oil produced in excess of about 800 B/D during the high

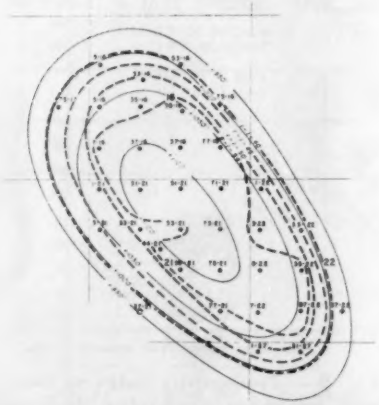

Fig. 6 — Positions of 5 per cent cut lines.

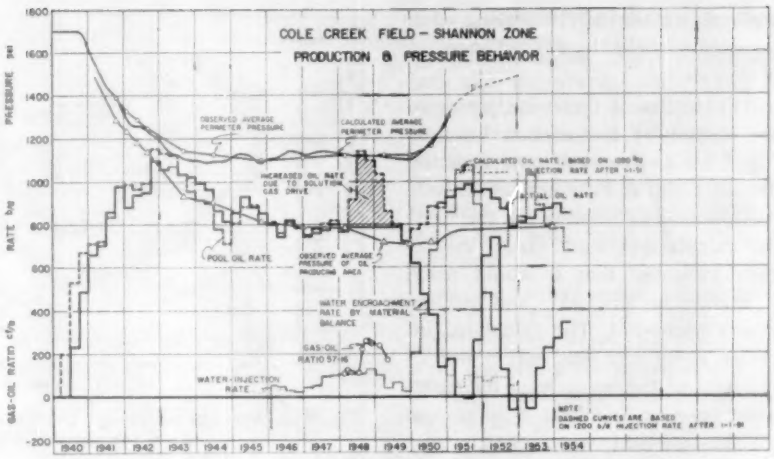

Fig. 7 — Production and pressure behavior.

rate period was by means of solution gas drive. This interpretation is shown on Fig. 7. In the second quarter of 1949 bubble point pumps were installed in practically all wells not already so equipped, and casingheads of practically all wells were shut in. Oil rate was reduced thereby to about 720 B/D in the fourth quarter of 1949.

In 1950 five wells were added to the water injection system making six total. By the fourth quarter of 1950 the net water encroachment rate dropped to 140 B/D, and the oil rate increased to 880 B/D. The average perimeter pressure increased from a level of 1,130 psi in Jan., 1950, to almost 1,300 psi in Jan., 1951.

On Fig. 8 the pressure difference between perimeter and oil producing area and average oil rates between pressure surveys are plotted vs the cumulative oil recovery from the pool.

Three factors affect the difference in pressure between the perimeter and the oil producing area: (a) proximity of the perimeter to the oil producing area, (b) the average oil rate being produced as the result of water encroachment, and (c) the increasing resistance to flow caused by encroached water and free gas in the sands between the perimeter and the oil producing area.

After 1943 the pressure difference plotted on Fig. 8 increased uniformly with the cumulative oil recovery from the pool. Most of the plot was established while the oil rate was nearly constant, about 800 B/D. The plot, therefore, gives a good evaluation of the combined effect of the factors of proximity and increasing resistance to flow. As mentioned before, the increase in oil rate during 1948 and 1949 is attributed to solution gas drive rather than water drive.

Calculations of Future Performance

As of Jan. 1, 1951, the future performance of the pool was calculated for a period of two years using three interdependent relationships: (1) the pressure difference relationship presented on Fig. 8, (2) the Hurst water-drive equation, and (3) the reservoir oil rate equation:

$$Q^o = (\overline{p}_{PA} - 500) \times \Sigma PI$$

where:

Q^o = Reservoir oil rate, B/D

$\overline{p}_{PA}$ = Average pressure of the oil producing area, psi

500 = Average producing pressure experienced with bubble point pumps, psi

ΣPI = Total oil productivity index of the producing wells, B/D/psi

As a first approximation, the pressure difference between the perimeter and the oil producing area was assumed to be proportional to the oil rate. Therefore, if the oil rate were to be increased, the difference in pressure would have to be increased proportionally. Pressure differences required for various oil rates are shown by dashed lines on Fig. 8.

In order to increase the oil rate of the pool without reducing producing pressures in individual wells, it was necessary to increase the average pressure of the oil producing area. Therefore, the increase in perimeter pressure to secure a given increase in oil rate is equal to the sum of the increase in pressure difference required on Fig. 8 and the increase in

pressure of the oil producing area required to yield the desired increase in oil rate.

The results of these computations are shown by the dashed lines on Fig. 7 for an assumed water injection rate of 1,200 B/D. Although oil rate was increasing rapidly at the time the calculations were made, the results indicated that it would reach a maximum in 1951 and decline slowly thereafter. The calculated increase in oil rate was only about 25 per cent of the increase in the water injection rate. In effect, a large part of the injected water rate would merely replace former natural water encroachment rate rather than increase the oil rate. It will be seen on Fig. 7 that the actual oil rate leveled out slightly below the rate calculated in 1951. The drop in actual rate shown in 1952 is attributed to the fact that the water injection rate fell far below the assumed value of 1,200 B/D (the water was used for another purpose).

Water Injection

Trial injection at 75-17 was carried on in 1944. Rate of injection was low and declined significantly, and trial injection was discontinued. An abandoned dry hole, 37-21, was selected for a continuous injection trial. The hole was cleaned out; 4½ in casing was run; the well was shot with nitroglycerin and put on the pump to clean out prior to measuring productivity index. Injection into 37-21 started in Feb., 1946, at a rate of 200 to 300 B/D with a tubinghead pressure of 350 psi. Injection into this well has continued up to the present time, and cumulative water injection as of Aug. 1, 1954, was about 720,000 bbl. Source of the water is a nearby well drilled to a relatively shallow fresh water zone. Initially this water was treated with alum and filtered, but after several years of operation the treating plant was by-passed. Water is now pumped through a closed system from the water well into 37-21. The water for the five other injection wells is produced from shallow fresh water sands into a closed system. Individual well injection pressures range from 0 to 90 psi. Total injection rate is shown on Fig. 7. As of Aug. 1, 1954, a total of 1,940,000 bbl of water had been injected into the reservoir. Because decline in injectivity indexes has been minor, no remedial work of any kind has been required in the injection wells.

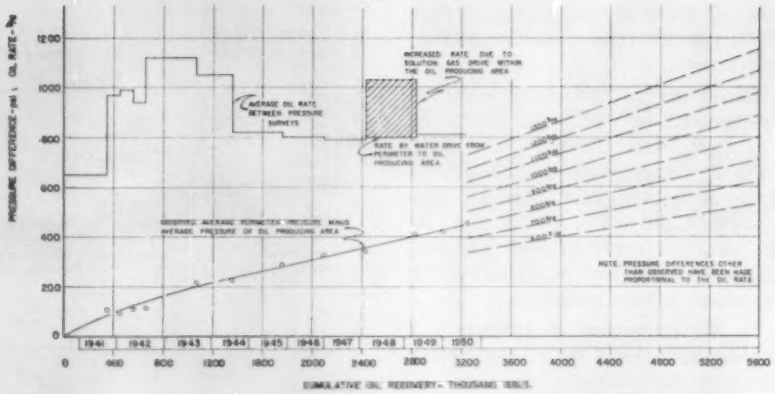

Fig. 8 — Average perimeter pressure minus average pressure of oil producing area for various oil rates vs cumulative oil.

Productivity Indexes

In the early life of the reservoir it became evident that well productivity indexes would have to be maintained at a satisfactory level for a long time in order to secure the reserve available without excessive development costs. Accordingly, studies were made of the causes of productivity index decline to determine possible preventive measures. Various means of increasing productivity indexes were also tried.

One common cause of productivity index decline is increase in gas saturation around the wellbore. Per cent of initial productivity index is plotted on Fig. 9 vs time after the producing pressure fell below the bubble point for 10 wells with minimum producing pressures less than 40 per cent of the bubble point. The declines in productivity indexes of these 10 wells were severe and rapid. The severity of the decline of four of these 10 wells was apparently increased by the proximity of encroaching water.

Productivity index in per cent of initial is plotted vs time after completion on Fig. 10 for 18 wells with minimum producing pressures more than 40 per cent of the bubble point. The data are scattered, but there is no general trend, up or down.

This study of all wells on which productivity index data trends are available strongly supports the conclusion that wells can be operated with producing pressures somewhat below the bubble point without serious decline in productivity index. However, if producing pressures are far below the bubble point, decline in index is apt to be rapid and severe. Losses in productivity index were only partially overcome by reducing rates after decline had taken place.

Shooting with Nitroglycerin

Use of solidified nitroglycerin to shoot the wells gave spectacular results at many wells. Experience is summarized on Fig. 11. Generally, wells which had suffered severe productivity index decline were shot. Just before shooting, eight of the 10 wells shown on Fig. 11 had productivity indexes less than 50 per cent of their initial values. In nine of 10 wells shot, the productivity index after shooting was many times the productivity index before shooting; and in eight of the 10 wells, the productivity index after shooting was higher than the original productivity index.

Bubble Point Pumps

The productivity index histories of the wells indicate that a policy of

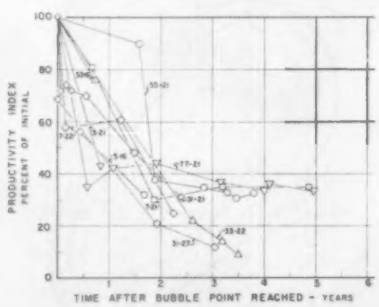

Fig. 9 — Productivity index vs time, with minimum producing pressure less than 40 per cent of bubble point pressure.

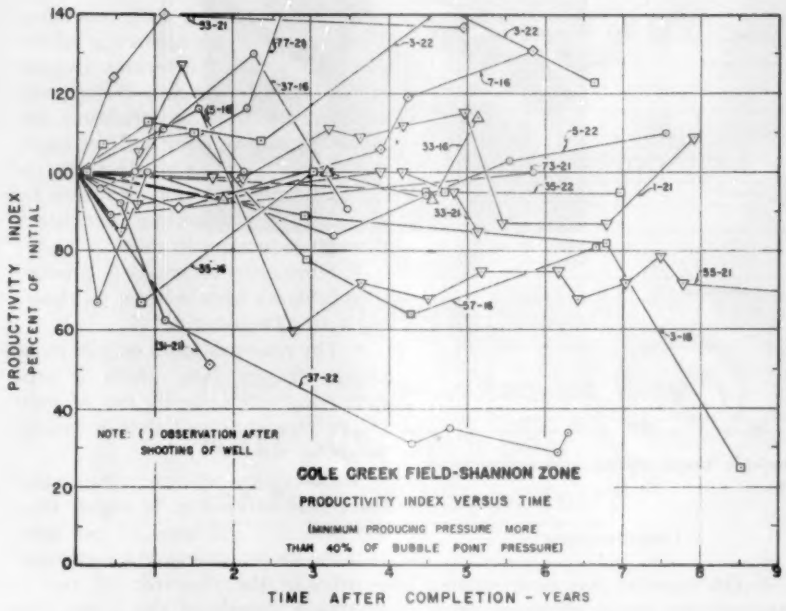
PRODUCTIVITY INDEX
PERCENT OF INITIAL
TIME AFTER COMPLETION - YEARS
NOTE: ( ) OBSERVATION AFTER SHOOTING OF WELL
COLE CREEK FIELD-SHANNON ZONE
PRODUCTIVITY INDEX VERSUS TIME
(MINIMUM PRODUCING PRESSURE MORE THAN 40% OF BUBBLE POINT PRESSURE)

Fig. 10 — Productivity index vs time, with minimum producing pressure more than 40 per cent of bubble point pressure.

maintaining relatively high producing pressures is desirable.

By far the most successful means of maintaining high producing pressures has been bubble point pumps. Designed by E. V. Watts, the bubble point pump is simply a standard pump with the addition of a 15-ft extension between the bottom of the pump barrel and the standing valve. This gives a large clearance volume and thus makes the pump very inefficient if any free gas is present in the pump. For proper operation it is necessary to shut in the casinghead, in order to force the pump to handle all of the free gas produced by the well. Because the annulus is entirely filled with gas, observation of the casinghead pressure then gives a direct means of determining the producing pressure of the well. Average producing pressure maintained by these installations is about 500 psi.

High rates were curtailed in 1949. Examples of the effectiveness of the bubble point pump in curtailing the rate are shown on Fig. 12. Gross rates and casinghead pressures at 31-21 during 1949 are shown at the top, and those of 57-16 are shown at the bottom. The gross rate of 31-21 was reduced from 80 B/D to less than 10 B/D, and the gross rate of 57-16 was reduced temporarily from about 125 B/D to less than 20 B/D. During June the casinghead pressure at 31-21 was reduced from 500 psi to 100 psi, and the rate increased to its previous high value. When the casinghead was shut in again, the rate dropped again to its previous low value. This type of performance was repeated frequently in the latter part of 1949 because of varying needs for gas.

Installation of bubble point pumps in all of the wells has resulted in automatic production of the maximum efficient rate of the pool.

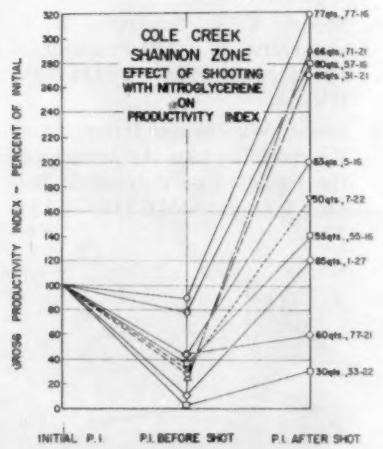

Fig. 11 — Effect of shooting with nitroglycerin on productivity index.

Performance of Edge Wells

The maximum daily production rate and the average daily rates of edge wells for the month just before shut in are shown in Table 1. It will be seen that two wells, 75-17 and 3-21, were shut in early in the life of the field. It is our present feeling that these two wells were shut in prematurely.

At five other wells which were shut in, 3-16, 53-16, 33-22, 1-27, and 31-27, the maximum gross rates were quite low before shut-in. Cuts of these wells were between 26 and 40 per cent; the highest gross rate was 10 B/D. Even though apparently overtaken by the encroaching water, these wells produced at low water rates.

Recovery Efficiency

Because wells outside the 5 per cent cut line produced negligible oil before Jan. 1, 1950, the position of the 5 per cent cut line on Fig. 6 can be used to estimate the water-drive efficiency. Based on Fig. 6, the core and fluid properties, and the cumulative oil recovery of 3.05 million bbl, a recovery efficiency by water drive to Jan. 1, 1950, of about 33 per cent is estimated. Per cent cut lines for Aug. 1, 1954, are shown on Fig. 13; nine wells were producing outside of the 5 per cent cut line. Their combined oil rate was 21 per cent of the reservoir total oil rate. Because of the increasing and significant per cent of the pool oil rate which is produced from outside the 5 per cent cut line, recovery efficiency ultimately may be somewhat higher than the 33 per cent calculated from the Aug. 1, 1954, cumulative oil of 4.52 million bbl and the corresponding 5 per cent cut line. Although 33 per cent recovery efficiency appears to be low for water drive, laboratory data tend to indicate relatively low recovery by water drive. These data are shown on Fig. 14. Note that oil recovery is 40 to 47 per cent at cuts below 80 per cent. Because most wells shut in to date were producing with rela-

TABLE 1 — EFFECT OF WATER ENTRY ON PRODUCTION RATE OF EDGE WELLS

Well Number	Maximum Daily Production Rate				Daily Production for Month Before Shut In				Present Status
	Gross B/D	Oil B/D	Cut %	Month	Gross B/D	Oil B/D	Cut %	Month	(As of 8-54)
3-16	76	76	0.1	Nov. 41	3.3*	2.5	26	Sept. 51	Abandoned
53-16	67	67	0.1	Dec. 42	2.3*	1.4	40	Nov. 47	Injection Well
75-17	78	75	4.0	Jan. 42	37	16	56	May 43	Injection Well
3-21	73	72	1.2	March 42	36	29	19	Oct. 43	Injection Well
33-22	74	74	0.4	Dec. 41	1.7*	1.3	38	April 48	Injection Well
1-27	28	27	1.9	July 45	2.5*	1.8	30	Oct. 47	Injection Well
31-27	81	81	0.4	April 42	10*	7	30	Dec. 49	Abandoned

*Represents maximum rate obtainable from well.

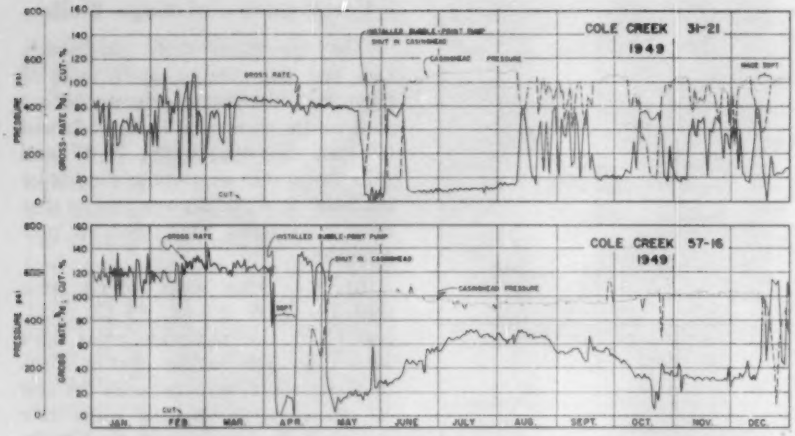

Fig. 12 — Examples of rate control by bubble point pump and casinghead pressure.

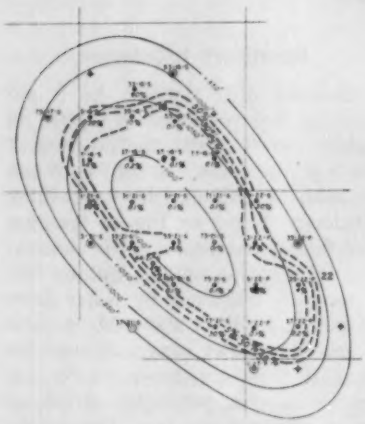

Fig. 13 — Per cent cut as of Aug. 1, 1954.

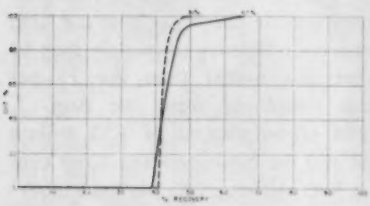

Fig. 14 — Water drive recovery-cut history obtained through laboratory tests.

tively low cuts, the low recovery portion of the laboratory data is probably applicable.

Conclusions

1. Oil recovery has been secured primarily by means of water drive, and at producing pressures above or slightly below the bubble point.

2. Water drive is stronger from the north and west than from the south and east.

3. Hurst's water-drive equation for an infinite aquifer was applied after about three years' history, and calculated pressures thereafter coincided with observed pressures for the following 10-year history.

4. The difference in pressure between the perimeter and the oil producing area required to secure a given oil rate by water drive is about proportional to the cumulative oil produced from the reservoir. Calculations of future performance, based on the pressure difference relationship, Hurst's water-drive equation, and the reservoir oil-rate equation, correctly indicated limitations on maximum oil rate which were not apparent before the calculations were made.

5. With net formation withdrawals reduced to about zero by water injection, only about one-fourth of the injected water rate serves to increase the oil rate. The remaining three-fourths of the injected water rate merely replaces former natural water encroachment.

6. Wells operated with producing pressures somewhat below the bubble point did not exhibit serious declines in productivity indexes. Wells operated with producing pressures far below the bubble point suffered rapid and severe losses in productivity indexes, which were not overcome by increasing producing pressures through reductions in rates.

7. Substantial increases in productivity indexes were secured by shooting with nitroglycerin.

8. The reservoir has a definite maximum efficient rate, which is produced automatically by use of bubble point pumps and shut-in casingheads.

9. Recovery efficiency by water drive may ultimately be higher than the presently indicated 33 per cent, because an increasing and significant portion of the reservoir oil rate is produced outside of the 5 per cent cut line which was used to determine the recovery efficiency.

Acknowledgments

The authors are indebted to D. T. Hoenshell for enthusiastically endorsing the preparation of the paper, providing the basic data, and reviewing the paper.

They wish to express their appreciation to E. S. Boyer and K. B. Green for their efficient assistance in the preparation of the paper.

Permission of the managements of the General Petroleum Corp. and Mobil Producing Co. to publish this paper is gratefully acknowledged.

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1. Whitaker, E. J., and Hoenshell, D. T.: "Sound Engineering Practices Increase Recovery Efficiency in Cole Creek Shannon Sand Reservoir," *Oil and Gas Jour.* (July 19, 1951) 95.
2. Moore, T. V., Schilthuis, R. J., and Hurst, W.: API Proceedings (Production) (May, 1943) 14M (IV), 4.
3. Hurst, W.: "Water Influx into a Reservoir and Its Application to the Equation of Volumetric Balance," *Trans.* AIME (1943) **151,** 57.

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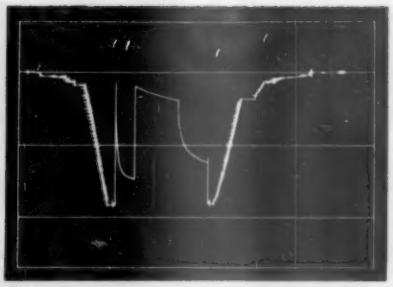

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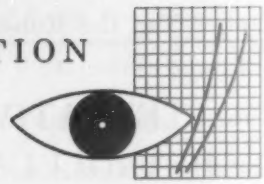
REPORT and INTERPRETATION



JOE B. ALFORD

EXECUTIVE SECRETARY
PETROLEUM BRANCH, AIME

30th PETROLEUM BRANCH FALL MEETING

The Petroleum Branch first initiated the practice of holding a meeting in October of each year in 1926. The records indicate that a meeting has been held each year since, thus making the meeting in New Orleans in Oct., 1955, the 30th Annual Petroleum Branch Fall Meeting.

The Petroleum Branch of AIME is by no means a stranger to New Orleans, as a major Fall Meeting was held there in October of 1950. The dynamic growth of the Petroleum Branch in the years since, however, will be reflected in the 1955 meeting, for which an attendance of over 2,000 men and 700 women is expected. This is in contrast to an attendance of 930 men and approximately 150 women in 1950. Members who attended the 1950 meeting remember the enjoyable social functions staged by the Delta Section as host, and those attending the meeting this year can look forward to the same.

Housing

To date approximately 1,450 hotel rooms have been assigned in New Orleans to persons requesting reservations. This is the maximum number of hotel rooms that the entire city could furnish for the meeting, and all reservations henceforth will be placed in motels. As one of the major resort cities in the South, New Orleans is blessed with a large number of good motels, some of which are located close to the downtown area.

Reservations requests received by the Housing Committee through July 1 include 708 ladies who are planning to attend the meeting. This large increase in women attendance reflects the keener interest of wives that has developed during recent years in the professional activities of their petroleum engineer husbands. The 1,450 hotel rooms thus far assigned compares to approximately 1,475 rooms used last year in San Antonio.

Technical Program

The technical program for the meeting promises to be unusually good this year. Under the chairmanship of L. P. (Barney) Whorton, director of production research for The Atlantic Refining Co. in Dallas, the Petroleum Branch Technology Committee has assembled an excellent group of papers for the program. The committee began work in January, and by early May 78 papers had been offered for placement on the program. From these, 45 papers were selected and manuscripts are now in preparation.

Preprints will be distributed on all possible papers in the usual package, but will *not* be distributed by package in advance of the meeting. An interesting note on the 1950 meeting in New Orleans was that after the registration on the evening before the meeting began, AIME members could be seen all over the French Quarter carrying envelopes of preprints. No doubt a similar advance distribution of preprints will take place again this year on Sunday evening after the beginning registration Sunday afternoon.

The technical program has been arranged in 13 one-half-day sessions. Ten of these sessions will be held in the Grand Ballroom and the new International Room of the Roosevelt Hotel, both of which have a ballroom seating capacity of over 1,000 persons. Two sessions will be held in the Orpheum Theater across the street from the Roosevelt Hotel, and one session will be held in the Ballroom of the St. Charles Hotel, three blocks away. Two concurrent sessions will be held each morning and afternoon except Wednesday morning, during which three concurrent sessions will be held. A full statement of all papers on the program and the sessions in which they are now arranged is published on pages 28 and 29 of this issue of PETROLEUM TECHNOLOGY.

Entertainment

The Delta Local Section, under the chairmanship of B. L. (Barney) Francis of The Texas Co., will be host to the Branch Fall Meeting. The section and meeting officers have been working since January in developing plans. Entertainment now scheduled on Monday includes the customary Welcoming Luncheon in the Ballroom of the Roosevelt Hotel for the men, and an afternoon sherry-coffee in the New Orleans Petroleum Club for the ladies. The section has reserved the Steamer President, which plys the Mississippi, for a boat ride for all members and ladies attending the meeting on Monday evening. The steamer will carry this party only. Beginning at 7 p.m. the Delta Section will stage a buffet supper and dance aboard the steamer during a trip of several hours along the river.

On Tuesday, Oct. 4, the Petroleum Branch Membership will participate in the second annual Membership Luncheon in the International Room of the Roosevelt Hotel, and the ladies will attend a style-show and luncheon in the ballroom of the Roosevelt. On Tuesday evening the Petroleum Branch Banquet and Dance, involving a probable attendance of 1,700 persons, will be held in the Ballroom and the International Room of the Roosevelt, with a local New Orleans band playing in each.

Those who attend the meeting will be likely to come away with something new on petroleum engineering and some wonderful memories of enjoyable social functions.

Advance Registration Discontinued

Advance registration for the Fall Meeting, which has been conducted in the past two years, has been discontinued. This advance registration for the 1954 Fall Meeting cost the Petroleum Branch $720 and only 407 members took advantage of it. The Branch Executive Committee did not feel this participation by members was adequate to justify the costs, and voted to discontinue the practice effective with the 1955 Fall Meeting. Coupled with this has been the development of a more efficient registration system at the meeting.

***

Oct. 2-5 at the Roosevelt Hotel

TENTATIVE PROGRAM of PAPERS and ACTIVITIES for PETROLEUM BRANCH FALL MEETING in NEW ORLEANS

Sunday, October 2

1:00 p.m. to 6:00 p.m. — REGISTRATION — University Room, Roosevelt Hotel

2:30 p.m. to 5:00 p.m. — AIME PETROLEUM SECTION CONFERENCE — Ballroom, Roosevelt Hotel

Monday, October 3

9:00 a.m. to 11:15 a.m. — PRODUCTION EQUIPMENT — Roosevelt Ballroom

501-G: *Plunger Lift Correlation Equations and Nomographs,* CARROL M. BEESON, University of Southern California

509-G: *A Flowmeter for Measuring Subsurface Flow Rates,* J. L. NEWMAN, H. L. SAUDER, and COURTNEY WADDELL, Lane-Wells Co.

528-G: *A Review and Analysis of Equipment for Running Electrical Cables Under Pressure,* A. C. H. COOKE, Lane-Wells Co.; F. L. SCOTT, JR., Dia-Log Co.; and CECIL GREER, Bowen Co. of Texas

9:00 a.m. to 11:45 a.m. — LOGGING — Roosevelt International Room

500-G: *Displacement Logging — A New Exploratory Tool,* W. M. CAMPBELL and J. L. MARTIN, The Atlantic Refining Co.

503-G: *Neutron Log Correction Charts for Borehole Conditions and Bed Thickness,* by J. T. DEWAN, Schlumberger Well Surveying Corp.

523-G: *Spectral Gamma-Ray Logging,* H. R. BRANNON, JR. and J. S. OSOBA, Humble Oil and Refining Co.

532-G: *Effect of Clay and Water Salinity on Electrochemical Behavior of Reservoir Rocks,* H. J. HILL and J. D. MILBURN, Shell Oil Co.

10:00 a.m. — LADIES WELCOMING COFFEE

12:15 p.m. — PETROLEUM BRANCH WELCOMING LUNCHEON — Roosevelt Ballroom

3:00 p.m. — LADIES SHERRY-COFFEE — Petroleum Club of New Orleans, Shell Building

2:15 p.m. to 5:00 p.m. — FLUID MECHANICS — Roosevelt International Room

502-G: *Displacement of Oil by Water Flooding — A Discussion of Laboratory Evaluation Methods, The Importance of Wettability, and Consideration of Other Important Variables,* T. F. MOORE and R. L. SLOBOD, The Atlantic Refining Co.

511-G: *Wettability Versus Displacement in Water Flooding in Unconsolidated Sand Columns,* JACK NEWCOMBE, JOHN MCGHEE and M. J. RZASA, Cities Service Research and Development Co.

518-G: *A Comparison of Field k_g/k_o Characteristics and Laboratory k_g/k_o Test Results Measured by a New Simplified Method,* W. W. OWENS, D. R. PARRISH, and W. E. LAMOREAUX, Stanolind Oil and Gas Co.

542-G: *Experimental Waterflooding Recoveries at Pressures Above and Below the Bubble Point,* D. M. BASS, JR. and PAUL B. CRAWFORD, Texas Petroleum Research Committee

2:30 p.m. to 5:00 p.m. — SLIM HOLE DRILLING — Roosevelt Ballroom

506-G: *An Engineering Appraisal of Small Diameter Hole Drilling in Soft Rock Operations,* J. H. FAULK, The Atlantic Refining Co.

512-G: *Slim Hole Drilling,* by P. L. MCLAUGHLIN, Cardwell Manufacturing Co., Inc.

529-G: *Development of Services and Equipment for Slim Holes,* T. A. HUBER, Humble Oil and Refining Co.

516-G: *New Developments in the Control of Lost Circulation,* P. P. SCOTT and J. L. LUMMUS, Stanolind Oil and Gas Co.

2:30 p.m. to 5:00 p.m. — INFORMAL CONFERENCE — ELECTRICAL LOGGING IN SHALY SANDS — St. Charles Hotel Ballroom

6:30 p.m. — FOR LADIES AND MEN — BUFFET SUPPER AND DANCE DURING STEAMER RIDE ON MISSISSIPPI — Delta Section, Hosts

Tuesday, October 4

8:30 a.m. to 11:15 a.m. — CEMENTING — Roosevelt International Room

508-G: *A New Material for Deep Well Cementing,* DWIGHT K. SMITH, Halliburton Oil Well Cementing Co.

519-G: *Problems in Casing Collapse,* G. N. MURCHEY, Creole Petroleum Corp.

522-G: *An Accelerated Squeeze-Cementing Technique,* G. K. DUMBAULD, D. PERRY, F. A. BROOKS, JR., and G. W. BINKLEY, Humble Oil and Refining Co.

530-G: *A New Retrievable Wire Line Cementing Tool,* BLAKE M. CALDWELL and GEORGE E. BRIGGS, JR., Welex Jet Services, Inc.

Advance registration will not be conducted for the Petroleum Branch Fall Meeting this year. The Petroleum Branch Executive Committee voted to discontinue advance registration because of the few members who were taking advantage of it and the expense involved in carrying it out. Further details of the meeting are published on page 27.

8:30 a.m. to 11:15 a.m. — ECONOMICS AND GENERAL INTEREST — Orpheum Theater

551-G: *The Near-Term Supply and Demand Outlook for the Petroleum Industry*, JOHN G. WINGER, Chase Manhattan Bank

552-G: *Objectives of Engineering Education*, WILLIAM V. HOUSTON, Rice Institute

541-G: *Northeast Butterly Pool — Case History*, ROY BUTLER, S. D. MCCLOUD and JACK MARSHALL, Continental Oil Co.

12:00 m. — LADIES LUNCHEON AND STYLE SHOW — Roosevelt Ballroom

12:15 p.m. — PETROLEUM BRANCH MEMBERSHIP LUNCHEON — Roosevelt International Room

2:30 p.m. to 5:00 p.m. — DRILLING — Roosevelt International Room

557-G: *Flow Properties of Suspension in Drilling Mud Design*, W. C. BROWNING, Marathon Corp.

505-G. *Effect of Mud Column Pressure on Drilling Rates*, A. S. MURRAY, Imperial Oil Ltd., and R. A. CUNNINGHAM, Hughes Tool Co.

525-G: *Lost Circulation Information Obtained with a New Tool for Detecting Zones of Loss*, T. BARDEEN and A. J. TEPLITZ, Gulf Research & Development Co.

540-G: *Development and Testing of Jet Pump Pellet Impact Drill Bits*, P. S. WILLIAMS, The Carter Oil Co.

2:45 p.m. to 5:00 p.m. — MODELS AND ANALOG COMPUTERS — St. Charles Hotel Ballroom

507-G: *The Determination of the Water Injection Program for the Delhi Field by Means of the Automatic Multi-Pool Analyzer*, O. L. PATTERSON, Sun Physical Research Lab., C. G. O. DUTTON and H. E. ELLIS, Sun Oil Co.

534-G: *An Analog Computer for Studying Heat Transfer During a Thermal Recovery Process*, L. C. VOGEL and R. F. KRUEGER, Union Oil Co. of California

537-G: *The Application of the Gelatin Model for Studying Effect of Mobility Ratio on the Performance of Horizontally Fractured Thin Reservoirs*, PAUL B. CRAWFORD and MELVEN BURTON, Texas Petroleum Research Committee

539-G: *Theory of Dimensionally Scaled Models of Petroleum Reservoirs*, G. A. CROES, J. GEERTSMA and N. SCHWARZ, Koninklijke/Shell-Laboratorium, Amsterdam

7:00 p.m. — PETROLEUM BRANCH BANQUET AND DINNER DANCE — Roosevelt Ballroom and International Room

Wednesday, October 5

8:30 a.m. to 11:45 a.m. — FLUID MECHANICS — Roosevelt Ballroom

510-G: *Influence of Rock and Fluid Properties on Immiscible Fluid Flow Behavior in Porous Media*, F. E. MERLISS, J. D. DOANE and M. J. RZASA, Cities Service Research and Development

517-G: *The Determination of Partial Pressure Maintenance Performance by Laboratory Flow Tests*, F. F. CRAIG, JR., and T. M. GEFFEN, Stanolind Oil & Gas Co.

536-G: *Mechanism of Water Flooding in the Presence of Free Gas*, J. R. KYTE, R. J. STANCLIFT, S. C. STEPHAN and L. A. RAPOPORT, The Carter Oil Co.

545-G: *Determining Gravity Drainage Characteristics on the Centrifuge*, J. W. MARX, Phillips Petroleum Co.

8:30 a.m. to 11:45 a.m. — WELL COMPLETION — Roosevelt International Room

526-G: *Control of Incompetent Sands Using Plastic Coated Walnut Shells*, J. K. HENDERSON, W. L. SALLEE, and C. M. STOUT, Dowell Incorporated

531-G: *Friction Loss of Fracturing Fluid*, THOMAS A. MATTHEWS II and C. O. BUNDRANT, The Western Co.

533-G: *Some Aspects of Sand-Oil Fracturing in Long Heterogeneous Sand Sections*, MARK F. NERO, International Petroleum Co., Ltd.

514-G: *Design of Casing Strings*, C. N. BOWERS, Gulf Research and Development Co.

8:30 a.m. to 11:15 a.m. — GAS TECHNOLOGY — Orpheum Theater

524-G: *Analysis of Low-Temperature Separation Plants*, H. E. STAMM, et al, Humble Oil and Refining Co.

538-G: *Investigation and Correlation of the Variables Affecting Separator Liquid Accumulation*, WILLIAM E. PORTMAN and JOHN M. CAMPBELL, The University of Oklahoma

544-G: *Simultaneous Flow of Liquid and Gas Through Horizontal Pipe*, A. F. BERTUZZI, M. R. TEK and F. H. POETTMANN, Phillips Petroleum Co.

1:30 p.m. to 4:30 p.m. — RESERVOIR ENGINEERING — Roosevelt Ballroom

513-G: *A Practical Method for Treating Oil-Field Interference in Water-Drive Reservoirs*, M. MORTADA, Magnolia Petroleum Co.

520-G: *Performance Calculations for Combination Drive Reservoirs*, N. J. CLARK and L. D. WOODY, JR., Humble Oil and Refining Co.

521-G: *Recovery of Oil by Condensing Gas Drive*, H. L. STONE and J. S. CRUMP, Humble Oil and Refining Co.

535-G: *Gas Drive and Gravity Drainage Analysis for Pressure Maintenance Operations*, D. R. SHREVE and L. W. WELCH, JR., The Carter Oil Co.

1:30 p.m. to 4:30 p.m. — PRODUCTION OPERATIONS — Roosevelt International Room

515-G: *Removal of Sulfides from Brine by Submerged Combustion*, W. J. HART et al, Gulf Oil Corp.

527-G: *Successful Conditioning of Pacific Ocean Water for Waterflood Injection*, J. D. SUDBURY, C. F. KNUTSON, MARTIN FELSENTHAL and J. D. LUNG, Continental Oil Co.

☆☆☆

NOMINEES for AIME OFFICES for 1957

In accordance with AIME by-laws, biographical sketches are given below of the men nominated by the 1955 Institute Nominating Committee for president, vice-presidents, and directors. Any additional nominations must be signed by 25 Members or Associate Members and sent to the Institute secretary by Sept. 1, 1955. A letter ballot will be mailed if such additional nominations are received. Each of the elected officers is to serve three years, with the exception of the president who will serve for one year.

For President

GROVER J. HOLT, general manager of the Ore Mining Dept. of Cleveland-Cliffs Iron Co., Ishpeming, Mich., has been nominated for the presidency in 1957. He received degrees in mining engineering from the University of North Dakota and did graduate work at the University of Utah. Following military service, he held positions with Bunker Hill & Sullivan Mining & Smelting Co., U. S. Steel Corp., and Manganiferous Iron Co. From 1930 until 1942 Holt was assistant to the vice-president of Butler Brothers. In 1942 he joined Cleveland-Cliffs as chief engineer. He is a past chairman of the Minnesota Local Section, the Minerals Beneficiation Div., the MBD annual fall meeting, and the Institute Nominating Committee.

For Vice-President and Director

JOSEPH LINCOLN GILLSON has been with E. I. duPont deNemours & Co. since 1930. He holds BS and MA degrees from Northwestern University and a MS degree from MIT. Before joining duPont, he taught at both Northwestern and MIT. Gillson is a past chairman of the Industrial Minerals Div. and the AIME Committee on Democratization. From 1951 until 1954, he was a vice-president of AIME.

LLOYD E. ELKINS has been associated with Stanolind Oil & Gas Co. since graduation from Colorado School of Mines. Now he is director of production research. In 1948 he attended the advanced management program at the Harvard Graduate School of Business Administration. In 1949 he was chairman of the Petroleum Branch, after serving as a local section chairman, Branch vice-chairman, and on the Executive Committee. Elkins has been an AIME director since 1953.

For Director

R. B. CAPLES is a nominee for another term as AIME director, after having just completed a three-year term. He is president and director of Anaconda Aluminum Co. Shortly after graduation from the Missouri School of Mines he began his career with Anaconda Copper Mining Co. In 1948 he received an honorary degree of Doctor of Engineering from the Missouri School of Mines.

C. R. DODSON has been active in the petroleum industry for the last 19 years. He is a graduate of the University of Maryland and MIT, and has done graduate work at the University of California. Prior to becoming assistant vice-president of the First National City Bank of New York City in 1954, Dodson held positions with General Electric Co., York Ice Machinery, Standard Oil Co. of California, the University of Southern California faculty, and as a petroleum consultant.

ANDREW FLETCHER, president of St. Joseph Lead Co., has held the positions of president, treasurer, and director of AIME. He has a PhB degree in mechanical engineering from Yale and an honorary degree of Doctor of Engineering from the University of Missouri. Fletcher also is president of Mine LaMotte Corp. and Bonne Terre Farming & Cattle Co.; vice-president of Missouri-Illinois R. R. Co.; and director of American-Hawaiian Steamship Co.

C. R. KUZELL is vice-president in charge of western activities for the Phelps Dodge Corp. and president of the Apache Powder Co. After graduation from Case School of Applied Sciences, he joined Anaconda Copper Mining Co. From 1918 to 1935 Kuzell was associated with United Verde Copper Co., then it became a part of Phelps Dodge Corp. The AIME member since 1912 was named to his present position in Jan., 1955.

FRED J. MEEK is plant engineer for the American Zinc Co. of Illinois. After attending the University of Illinois and serving in World War I, he worked with Egyptian Coal and Mining Co. and O. K. Coal Co. Later he held a position with Lawsonia Realty Corp., then joined Eagle-Picher Lead Co. in 1932. After becoming plant engineer for American Zinc in 1941, Meek was put in charge of engineering and later became superintendent of the Power and Mechanical Depts.

GAIL F. MOULTON, AIME treasurer, has been renominated for a three-year term as an AIME director. After graduation from the University of Chicago, he was assistant professor at the University of South Dakota, head of the petroleum section of the Illinois State Geological Survey, and with United Gas Co., Electric Bond & Share Co., and Ralph E. Davis, Inc Since 1951 he has been with Rockefeller Brothers, Inc., in New York City. ★★★

PROPOSED LETTER SYMBOLS for ELECTRIC LOGGING

A program to standardize letter symbols for use in mathematical expressions was undertaken by the Petroleum Branch in 1951 with the appointment of a committee to consider symbols for reservoir engineering. In 1952 a subcommittee was formed, consisting of H. G. Doll, chairman, A. A. Perebinossoff, and Milton Williams, to develop a set of logging symbols.

The Logging Subcommittee has prepared a list of proposed electric logging symbols which has been approved for publication in this issue by the Branch Executive Committee. The Executive Committee has also allowed the Logging Subcommittee until Jan. 15, 1956, to make alterations in the list. Accordingly, all members of the Petroleum Branch are invited to submit comments and suggestions on the list which appears below. These comments should be addressed to:

Symbols Committee
Petroleum Branch, AIME
800 Fidelity Union Building
Dallas 1, Tex.

On the basis of suggestions received, the Logging Subcommittee will revise the list and submit it to the Executive Committee for adoption as a standard.

This request for comments parallels that which was issued when the proposed list of reservoir engineering symbols was published in January, pages 37 to 39. The reservoir engineering list was accompanied in the January publication by a list of guides adopted by the Symbols Committee in selecting specific symbols, and by a formal statement of general principles of standardization. These guides and general principles apply equally to the proposed electric logging list below.

In order to conform to symbols chosen by the main Symbols Committee for the reservoir engineering list, the Logging Subcommittee has selected two symbols, f for porosity and σ (sigma) for conductivity, which do not represent the preferences of the subcommittee members, who would rather use ϕ (phi) and C respectively. On the other hand, the subcommittee has been unwilling to go so far as to abandon R for resistivity in order to be consistent with the reservoir engineering list, where ρ (rho) is used.

English		*Dimensions**
r	resistance	mL^2/tQ^2
R	resistivity	mL^3/tQ^2
R_a	apparent resistivity	mL^3/tQ^2
R_i	average resistivity of invaded zone	mL^3/tQ^2
R_{xo}	resistivity of invaded zone close to the wall of the hole, where flushing has been maximum	mL^3/tQ^2
R_m	mud resistivity	mL^3/tQ^2
R_{mc}	mud cake resistivity	mL^3/tQ^2
R_{mf}	mud filtrate resistivity	mL^3/tQ^2
R_w	in the laboratory: resistivity of an electrolytic solution in the field: resistivity of interstitial water	mL^3/tQ^2
R_z	resistivity of a mixture of two solutions	mL^3/tQ^2
R_o	resistivity of a formation 100 per cent saturated with water of resistivity R_w	mL^3/tQ^2
R_t	true formation resistivity	mL^3/tQ^2
R_s	resistivity of surrounding formations	mL^3/tQ^2
I	resistivity index—equals R_t/R_o	
F	resistivity formation factor in general—equals R_o/R_w. (Numerical subscript indicates value of R_w. For example, $F_{0.2}$ represents the value of formation factor measured with $R_w = 0.3$.)	
F_o	limiting value of resistivity formation factor when R_w approaches zero	
f	porosity	
m	formation resistivity factor exponent	
k	permeability	L^2
p	pressure	m/Lt^2
T	temperature	T
S	saturation	
S_w	water saturation	
S_o	oil saturation	
S_g	gas saturation	
n	saturation exponent	
H	gross pay thickness	L
h	net pay thickness	L
e	individual bed thickness	L
t_{mc}	mud cake thickness	L
d	hole diameter	L
D_i	electrically equivalent diameter of the invaded zone	L
E	potential difference	mL^2/t^2Q
E_c	electrochemical component of the spontaneous electromotive force, equals the electrochemical component of the spontaneous potential (self potential) when the bed is thick	mL^2/t^2Q
E_k	electrokinetic component of the spontaneous electromotive force, equals the electrokinetic component of the spontaneous potential (self potential) when the bed is thick	mL^2/t^2Q
K	coefficient in the equation of the electrochemical component	mL^2/t^2Q
Greek		
α alpha	spontaneous electromotive force reduction factor equals the spontaneous potential (self potential) reduction factor when the bed is thick: ratio of the value of E_c for a given shaly sand to the value of E_c for a clean sand having the same connate water	
σ sigma	conductivity	tQ^2/mL^3

*In the dimensional formulas m = mass, L = length, t = time, T = temperature, Q = electrical charge.

ROCKY MOUNTAIN PETROLEUM SECTIONS HOLD OUTSTANDING MEETING

The precedent for an annual joint meeting of the Petroleum sections of AIME in the Rocky Mountain region was launched with the first such meeting in Denver, May 26-27. Some 330 men registered for the meeting, and it was also attended by a number of ladies.

Eleven papers were presented on the two-day technical program. Interest of those attending the meeting in this program and the social functions remained high throughout the meeting.

Richard W. French, vice-president and general manager of Sohio Petroleum Co., and 1951 Petroleum Branch chairman, spoke to about 150 persons attending the Welcoming Luncheon on the subject "Where Is AIME Going?" The purpose of his talk was to point up the fact that petroleum engineering is not an art based upon one college curriculum. Rather it is a unification of several engineering skills and sciences, and that our real strength in AIME is the application of these to our common activity of oil production. Under this broad concept petroleum engineering and the Petroleum Branch of AIME can continue its healthy growth in the future. Further, because of the natural association of three branches of engineering to the extraction of mineral resources, AIME will continue to grow and render respected public service as the professional society for these fields.

Fourteen exhibitors participated in the meeting. A luncheon and style show was attended by approximately 60 ladies, and a dinner-dance on Friday evening was attended by some 165 persons. At the conclusion of the meeting it was decided to make the Joint Meeting of AIME Rocky Mountain Petroleum Sections an annual affair, and plans are being made now to hold the meeting next year in Casper, Wyoming.

JOE B. ALFORD

A scene at the banquet and dance is pictured at top left. A portion of those attending a technical session is shown at center left. Officers for the meeting (at bottom) are, left to right: Donald F. Brown, Jr., Sharples Oil Corp., arrangements; Billy F. Burke, Carter Oil Co., registration; Dale R. Worth, Continental Oil Co., arrangements; Paul E. Grimm, The Texas Co., entertainment; R. L. Hoss, Vaughey & Vaughey, general chairman; E. A. Polumbus, Jr., Polumbus Engineering, entertainment; Obie L. Stalcup, Halliburton, publicity; and John W. Tynan, Continental Oil Co., program.

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AT YOUR
PRODUCTION
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SCHLUMBERGER

SIDE-WALL CORING

Schlumberger
Side-Wall Coring

Oil operators everywhere are familiar with Schlumberger Side-Wall Cores. Used widely in unconsolidated areas, they are recognized as one of the most efficient and reliable sources of reservoir information. This is best evidenced by the fact that more than 1,000,000 cores have been sold to the Industry since the method was introduced in 1936. Many oil fields have been found or confirmed by Schlumberger Side-Wall Cores.

With the addition of the "hard formation" bullet to the Schlumberger Side-Wall Coring device, consolidated formations previously considered too hard for side-wall core recovery are now yielding cores of substantial length which are more than adequate for commercial analysis.

---

the pictorial study of cores

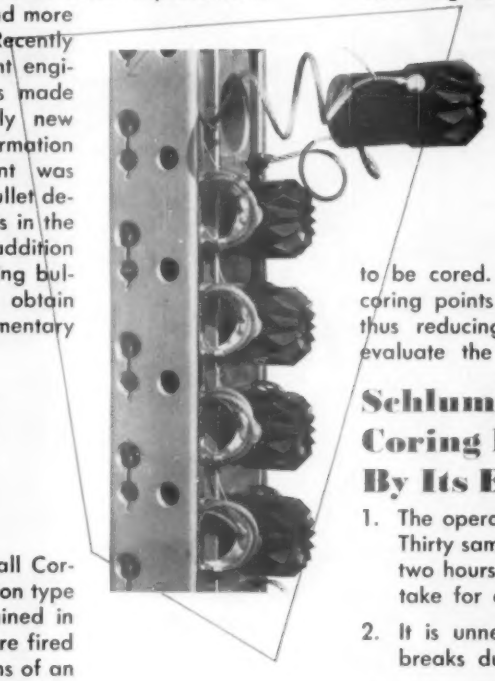
On the following pages, you will find life-size pictures of typical cores taken with the Schlumberger Side-Wall Coring Tool. All oil producing areas of the United States are represented. Regardless of where your drilling operations are located, you will find a picture indicating the amount of recovery you may anticipate in one or more of your possible producing horizons.

If It Will Produce, Schlumberger Can Core It

During the many years of service to the Petroleum Industry, improvements in design and operation have progressively appeared in the Schlumberger coring device. Two obvious results of these improvements have been larger cores, and more cores per trip in the hole. Recently a third and very important engineering advancement was made which opened an entirely new area of activity . . . hard-formation coring. This advancement was made possible by a new bullet design in addition to changes in the instrument itself. With the addition of the hard-formation coring bullet, it is now possible to obtain cores in almost all sedimentary formations.

The Schlumberger Side-Wall Coring Device

The Schlumberger Side-Wall Coring Instrument is a percussion type tool. Hollow bullets contained in barrels in the instrument are fired into the formation by means of an explosive charge which is electrically fired by controls at the surface. The degree of penetration is governed by: (1) Varying the amount of explosive in the barrel; (2) The type of bullet.



Schlumberger Hard Formation Coring Bullet

The bullets and contained cores are recovered from the formation by a retrieving cable (or wires) connected to the body of the instrument. Up to 30 cores can be obtained on one trip in the hole at specified depths. The bullets are fired in sequence upward from the bottom of the gun and are positioned accurately by using the S. P. curve of the electrical log as an absolute depth reference. After each core is taken, it hangs downward at the end of the retrieving cable without interfering with the next shot.

The Selection Of Side-Wall Coring Points

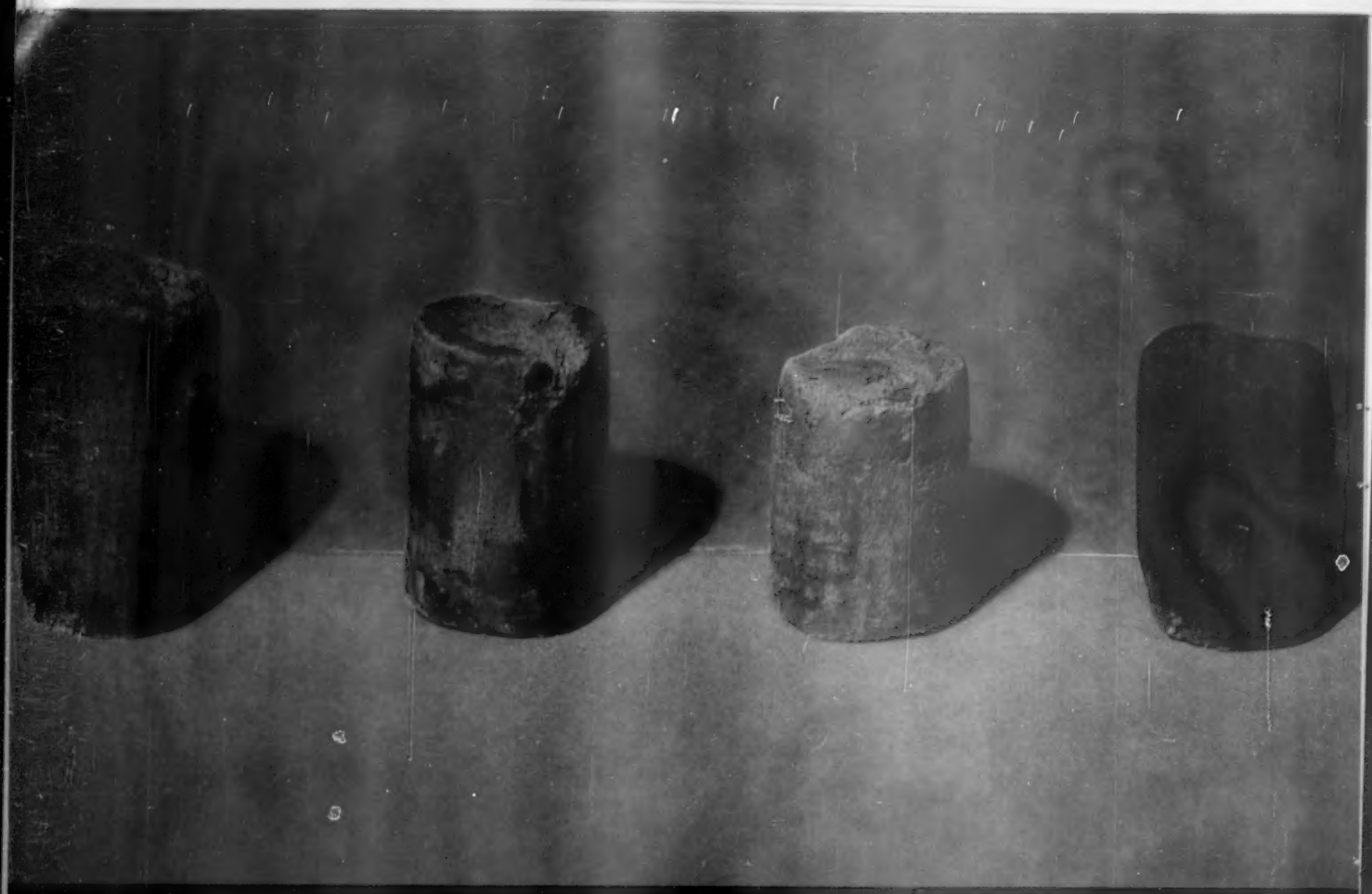
It has become standard practice to use both the Schlumberger Electrical Log and the MicroLog in the selection of proper coring points in a well. The Electrical Log indicates the possible producing zones, and accurately controls the placement of shots. Depth control is accomplished by adjusting the side-wall core depths to the Electrical Log depths directly through correlation of a second S. P. curve, observed in conjunction with the coring operation. The MicroLog is used to precisely identify permeable intervals in the zone which is to be cored. It aids materially in the selection of coring points by eliminating unproductive intervals, thus reducing the number of shots necessary to evaluate the zone.

Schlumberger Side-Wall Coring Is Highlighted By Its Economy

1. The operation of the Schlumberger tool is rapid. Thirty samples can be taken at 10,000 feet in only two hours. This is less than half the time it would take for a round trip with the drill pipe.
2. It is unnecessary to watch carefully for coring breaks during the drilling operation.
3. The cores cost very little compared to conventional, wire line or diamond coring.
4. Cores are taken in conjunction with electrical logging operations so there is no rig time involved except for the coring operation itself.
5. Pin-point accuracy is assured; the cores are obtained at exactly the desired depth by using the S. P. curve as a direct reference.
6. Cores are sufficiently large for a complete core analysis. Many commercial core laboratories are equipped to handle Schlumberger cores and the number of such analyses is rapidly increasing.
7. Cores are being used more and more in lithological and paleontological studies. Many shale and other cores are taken for this purpose.

Coring Device Dimensions

	Large Sample Taker		Standard Sample Taker	
	30-shot gun	*24-shot gun*	*18-shot gun*	*6-shot gun*
Minimum hole size	7 1/2"	6 1/4"	6 1/2"	5 1/2"
Core dimensions:				
Soft formation bullet — diameter	1 3/16"	1"	3/4"	3/4"
Maximum length —	2 1/4"	1 3/4"	2 1/4"	2 1/4"
Hard formation bullet — diameter	13/16"	13/16"	—	—
Maximum length —	2 1/4"	1 3/4"	—	—



LIBERTY, TEXAS
Miocene @ 2300′
30% Porosity

LAUREL, MISSISSIPPI
Lower Cretaceous @ 9000′-12,000′

Left to Right:	Porosity
Rodessa	16%
Rodessa	16%
Lower Glen Rose	18%
Lower Glen Rose	18%
Unnamed	20%
Unnamed	20%

EVANSVILLE, INDIANA
Mississippian @ 2150′

Left to Right	Porosity
Benoist SS	13%
Benoist SS	13%
Benoist SS	13%
Mississippian @ 2300′	
McClosky Lime	12%
McClosky Lime	12%

FARMINGTON, NEW MEX.
Lower Cretaceous @ 2200′

Left to Right:	Porosity
Pictured Cliffs SS	10%
Pictured Cliffs SS	12%

ABILENE, TEXAS
Permian @ 2100′

Left to Right:	Porosity
Dothan SS	15%
Permian @ 2400′	
Tannehill SS	15%
Permian @ 1600′	
Fresh Water SS	22%

CASPER, WYO.
Cretaceous @ 3000′

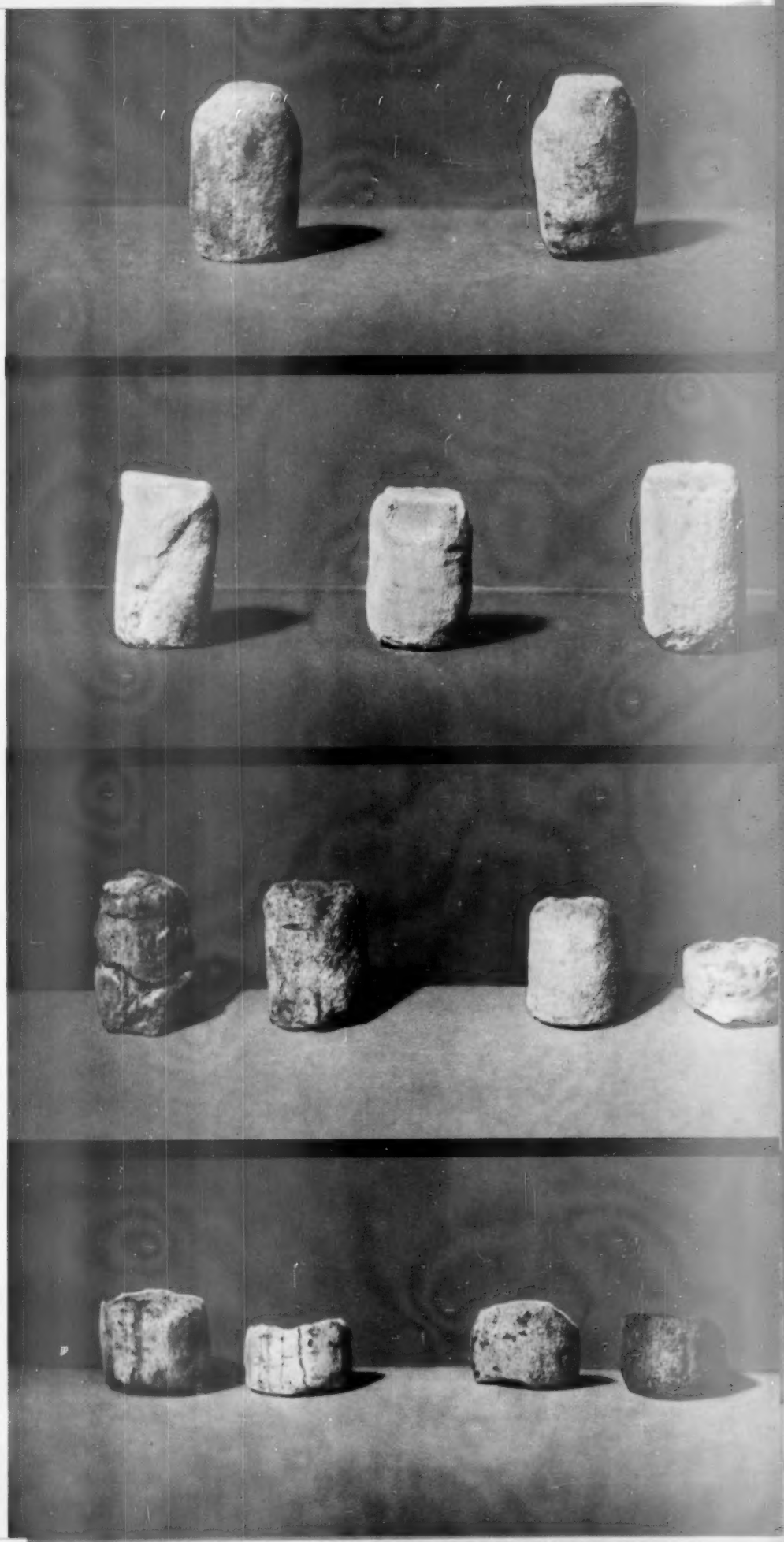
Left to Right:	Porosity
Muddy Sandstone	12%
Muddy Sandstone	12%

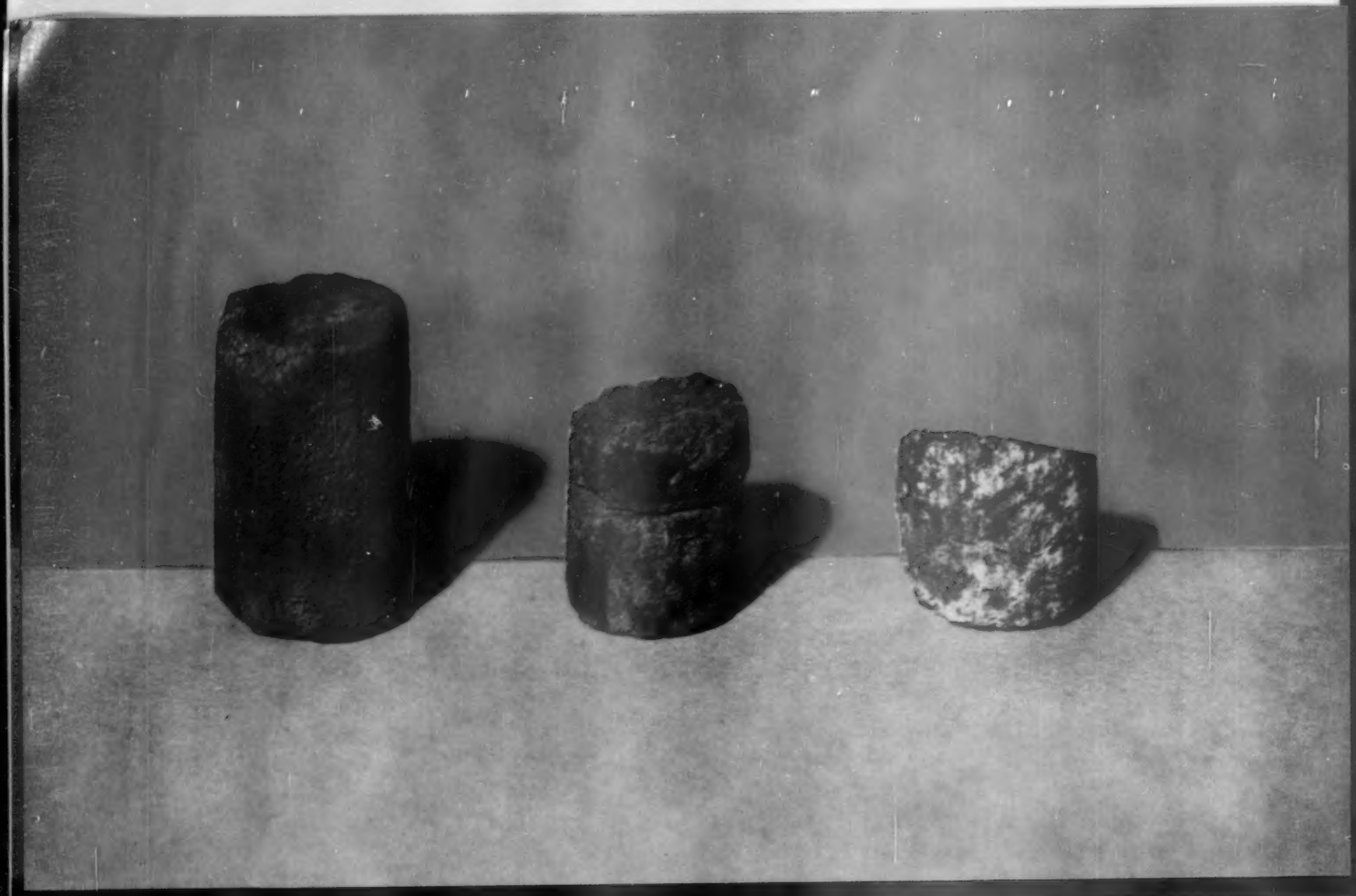
NEWCASTLE, WYO.
Cretaceous @ 5000′

Lakota Sandstone	20%
Lakota Sandstone	20%

LAUREL, MISSISSIPPI
Lower Cretaceous @ 9000′-12,000′

Left to Right:	Porosity
Paluxy SS	20%
McAlpine SS	20%
Bailey SS	14%
Bailey SS	14%





BAKERSFIELD, CALIF.
Miocene @ 1200′

Left to Right:	Porosity
Watersand	26%
Watersand	26%
Miocene @ 3200′	
Valz SS	26%

ABILENE, TEXAS
Penn. @ 5000′

Reef Lime	9%
Ordovician @ 4200′	
Ellenberger	10%
Penn. @ 3600′	
Caddo Lime	10%
Penn. @ 2900′	
Upper Fry SS	14%

DUNCAN, OKLAHOMA
Permian @ 2700′

Left to Right:	Porosity
Noble-Olson SS	12%
Noble-Olson SS	12%
Noble-Olson SS	13%
Noble-Olson SS	13%

WHARTON, TEXAS
Frio SS @ 7400′

Left to Right:	Porosity
	30% to 33%
	30% to 33%

Miocene SS @ 3500′

	32% to 35%
	32% to 35%
	32% to 35%

COLUMBUS, TEXAS
Eocene @ 9700′

Left to Right:	Porosity
Wilcox SS	13% to 18%
Wilcox SS	13% to 18%
Wilcox SS	13% to 18%

WICHITA, KANSAS
Penn. @ 2800′

Left to Right:	Porosity
Layton SS	20%
Layton SS	18%
Layton SS	20%

TULSA, OKLA.
Penn. @ 1800′

Unnamed SS	20%
Unnamed SS	20%

CUSHING, OKLAHOMA

Cleveland SS	20%

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MEMBERSHIP REGULATIONS

VIRGINIA B. DAGGETT | ASSISTANT SECRETARY PETROLEUM BRANCH, AIME

Magazines for Members Called to Military Service

Members and Student Associates called into military service may now receive the JOURNAL OF PETROLEUM TECHNOLOGY without charge for the duration of their active duty.

Formerly, a member inducted into military service could be transferred to "Inactive Status Because of Military Service." Dues payments and publications would be suspended temporarily, but he would retain his original election date and could be reactivated upon request as soon as he was released.

The Executive Committee of AIME at its May meeting voted to rename this "Service Status," and to send the desired monthly journal to the member free of charge if he specifically requests it. Each member presently registered as inactive was to be contacted to determine whether he wishes the journal, and he will be asked to reaffirm his wish annually, so long as he is in service.

Service Status can be granted only upon request of the member, and must be approved by the Board of Directors. It is the member's responsibility to keep in touch with the AIME if his address changes, and to request reactivation immediately after he is released from the service. This special provision is intended for the benefit of young men serving their required term of military duty, and not for members who choose the military as a career.

Graduating Students

Student Associates graduating this spring and summer are urged to notify the AIME of their new company affiliations and mailing addresses as soon as possible. It is not necessary to file an application for change of status to Junior Member. Students who have been graduated during this calendar year will be automatically transferred to Junior Member at the end of the year. It is important, however, that we have a correct mailing address on record at that time. Students who planned to graduate this year should notify AIME if they will remain in school longer. A student's anticipated date of graduation is taken from his original application for AIME records, and any later change in plans should be forwarded to the secretary's office.

Junior Members Reaching Age 33

A Junior Member who passes his 33rd birthday during this calendar year will be required to change status to a higher grade at the end of the year, unless he joined AIME with a military service exemption after he was 30 years of age.

Junior Members who have reached the maximum age will automatically be transferred to Associate Member status at the end of the year. Those who have the qualifications for Member should complete a change of status application, with full career data and three member endorsements. This may be submitted either before or after the automatic transfer to Associate Member. An initiation fee of $20 is due upon transfer into either Associate Member of Member status, whichever occurs first. A credit of $2 is extended toward this fee for each previous year of continuous membership as a Student Associate or Junior Member. The balance due may be paid in $5 annual installments if desired.

Proposed for Membership, Petroleum Branch, AIME

TOTAL AIME membership on April 30, 1955, was 22,499; in addition 1,687 Student Associates were enrolled.

PETROLEUM BRANCH ADMISSIONS COMMITTEE

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The Institute desires to extend its privileges to every person to whom it can be of service, but does not desire as members persons who are unqualified. Institute members are urged to review this list as soon as possible and immediately to inform the Secretary's office if names of people are found who are known to be unqualified for AIME membership.

In the following list C/S means change of status; R, reinstatement; M, Member; J, Junior Member; A, Associate Member; S, Student Associate.

California
Compton — O'Keeffe, John Joseph (R, C/S-A-M).
Downey—Markham, Wendell Glenn (M).
Garden Grove—Newman, Ronald Hudson (M).
Long Beach—Voorhees, Thomas Allen (J).
Whittier—Schurman, Glenn August (M).

Illinois
Mattoon—Schauer, Paul Emerson, Jr. (M).

Kansas
Hoisington — Abraham, Olin W. (R, C/S-S-A).
Russell—Sigurdson, Elden Arlo (J).
Wichita—Pitchford, Albert Lucian (M).

Louisiana
Golden Meadow—Walters, Jack Willard (M).
Shreveport—Oldham, Forrest Robert, Jr. (M).

Minnesota
Minneapolis—Marr, Thomas Oliver (J).

Montana
Glendive—Dingfelder, Clyde Allen (A).

Nebraska
Sidney—Simonsen, Kenneth N. (J).

New Mexico
Hobbs—Nevill, Benjamin (M).
Santa Fe—Utz, Elvis Adam (M).

New York
New York—Sterne, William P. (A).
Phoenecia — Atwater, Richard Mead, III (R, M).

Oklahoma
Ardmore—Tune, James Lewis, Jr. (J).
Bartlesville—Bergman, William Erving (M).
Duncan—Garrett, Lilburn Hodge (J); Smith, Dwight Kirby (M).
Healdton—Bamford, Robert James, Jr. (J).
Oklahoma City—Matthews, Sam Joe (M).
Tulsa — Clark, Thomas Arthur (M); Green, William Gladstone (R, M); Hinson, Billye J. (R, C/S-J-M); Millar, Peter James (M); White, Millage Miller (J).

Texas
Alta Loma—Lohec, Ronald Eugene (J).
Bellaire—Clegg, Millard Fillmore, Jr. (J); Horn, John (M); Ormsby, George Stonewall (M); Quay, Albert Harrison (M).
Bishop — Christofferson, Robert King (J); Gilstrap, Tommy O. (C/S-J-M); Leissner, Edgar L. (M).
Conroe—Lamberson, Jack Landis, Jr. (M); Smart, Samuel B. (J).
Corpus Christi—Bakke, Wilbur E., Jr. (J); Dudley, Bill M. (J); Hebert, Francis Julius (M); Hopson, Joseph William (M); Kahn, Harry Bradley, Jr. (M); Magee, Clarence O. (M); Osborne, Thomas Lloyd (M); Pearson, Hubbard Hugh (A); Phillips, J. D. (J); Stewart, Douglass Murray (M).
Dallas—Hoipkemeier, Fredrick Loual (M).
Fort Worth — Augustson, Arvin Willmore (J); Briggs, George Edwin, Jr. (M); McDuff, Charles Homer, Jr. (J).
Houston — Adler, Joseph Leopold (R, M); Brown, Joe Russell (M); Carlson, Karl William (J); Castel, Jacques Honore (M); Cooper, Theodore W. (A); Daigle, J. D. (J); Gealy, Fred Daniel, Jr. (J); Greaney, John Edward (J); Huston, Gilmer P. (M); Martin, Neil B. (M); Peters, Beldon Alfred (J); Robison, Kenneth Orr (M); Smith, John Douglas (M); Taylor, Joseph Williams (A); Viney, Ralph H. (M); Woollett, LeRoy (R, C/S-S-M); Worley, James Ellis (A).
Liberty—Engelke, Clarence Paul (J).
Midland—Burnett, Peter Geddes (C/S-A-M); Shoemaker, Robert Vernon (M).
Pasadena—Russell, James Harold (M).
Pettus—Dupree, Francis Edward (J).
San Antonio—Caran, Samuel Harry (R, C/S-S-M).

Utah
Salt Lake City—Schultz, Norman West (M).

Wyoming
Casper—Sweeney, Vincent Patrick, Jr. (J).
McFadden—Parker, Raymond Wallace (M).

Canada
Calgary, Alta.—Bebensee, Lloyd Wilfred (M).

Colombia
Barranquilla—Trassard, Jean Francois (M).

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TECHNICAL BULLETIN ISSUE

Again this year technical sales bulletins will be published in the September Fall Meeting Issue of JOURNAL OF PETROLEUM TECHNOLOGY. This policy of publishing "technical bulletins for technical men" received acclaim among Petroleum Branch members after being inaugurated in the 1954 September issue.

The binding of technical bulletins into the magazine is considered by the Branch Advertising Committee as a service to both advertisers and members. The closing date for insertion of these bulletins is Sept. 1, 1955.

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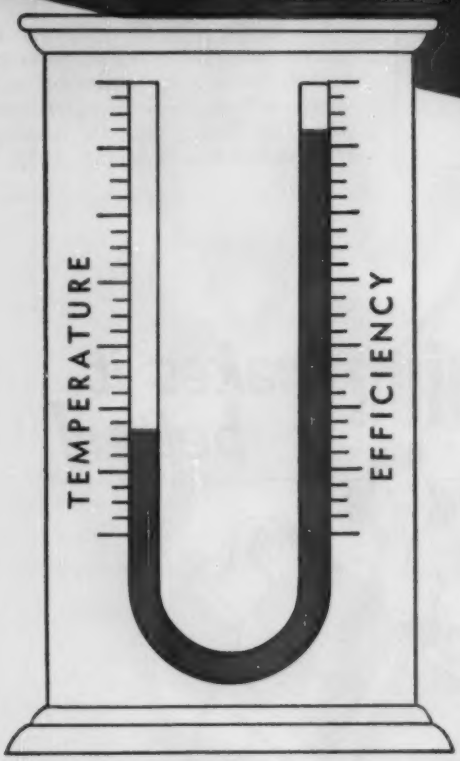

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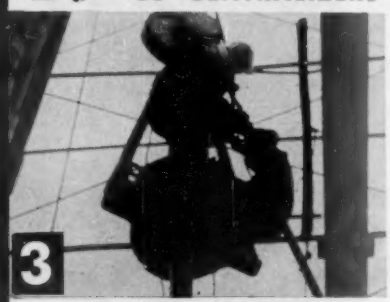

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MEET the AUTHORS

A picture and biographical sketch of LEENDERT DE WITTE were published in the April, 1955, issue of JOURNAL OF PETROLEUM TECHNOLOGY.

K. S. KUNZ is a research physicist on the staff of the Research Laboratory of Schlumberger Well Surveying Corp., Ridgefield, Conn. After receiving his PhD degree in physics from the University of Cincinnati, he taught there and at Harvard University until 1949. Then he was associate professor of electrical engineering at Case University until joining the staff of Schlumberger in 1951.

MAURICE PIERRE TIXIER is chief development engineer at the Houston headquarters of Schlumberger Well Surveying Corp. He is a graduate of Ecole d'Arts et Metiers d'Erquelinnes (Belgium) in 1932 and Ecole Superieure d' Electricite, 1933. He started to work for Schlumberger in 1935. From 1941 to 1949 he was manager of the Rocky Mountain area, then was appointed chief engineer of the company. In 1952 he assumed his present position.

PENN STATE FELLOWSHIP

The closing date for one of the Pennsylvania State University fellowships has been changed to Aug. 15, 1955. Established by Gulf Research and Development Co., the stipend is $2,000 per academic year plus payment of tuition and fees. The fellow will be a candidate for the doctor's degree in petroleum and natural gas engineering.

Applications should be addressed to John C. Calhoun, College of Mineral Industries, University Park, Pa. Material sent should include: name, age, citizenship, marital status, complete record of training including transcripts, three letters of recommendation, and a statement of extracurricular activities and industrial experience.

Necrology

Earl J. Robishaw, 44, vice-president of A-1 Bit and Tool Co. died in Houston on June 4. He was born in Saratoga, Tex., married, and the father of two children. After graduation from Texas A&M he worked for The Texas Co. and had been with A-1 for 18 years.

Date Elected	Name	Date of Death
1952	Allen, G. E.	Unknown
1948	Bartram, John G.	Feb., 1955
1930	Caster, Ermil Leslie	April 22, 1955
1943	Herring, Lafayette	March 3, 1955

San Joaquin, New York Sections Choose Officers

New officers to serve from June, 1955, to June, 1956, have been elected by the San Joaquin Valley Section. W. J. Taylor, Lane Wells Co., is the chairman. Other officers are: R. H. Adams, Standard Oil Co. of California, vice-chairman; H. L. Case, Core Laboratories, Inc., secretary; W. B. Emery II, Ohio Oil Co., treasurer; and K. R. Evans, petroleum consultant, membership.

The New York Petroleum Section, almost one year old, has elected officers for 1955-56. Dale Nix of Arabian American Oil Co. was selected as president, and E. M. Connaughton, Socony Mobil Oil Co., as secretary-treasurer. Chosen for the Section Executive Committee were: Bob T. H. Hulsey, Chase Manhattan Bank; Zeb Mayhew, Standard Oil Co. of New Jersey; H. E. McAuliffe, Jr., Socony Mobil Oil Co.; and Earl M. Rees, Byron Jackson Co.

Building Decision Delayed

The AIME Board of Directors has agreed to a proposal that a further study be made of the best location for a new engineering building, the Pittsburgh offer meanwhile being held in abeyance. A full report will appear in the August issue.

PERSONALS

C. E. REISTLE, JR., (left) AIME president-elect, has been elected vice-president of Humble Oil & Refining Co. RALPH J. SCHILTHUIS has been nominated for the Humble board of directors. Reistle joined Humble in 1936 as assistant chief petroleum engineer, having worked prior to that time as chairman of the East Texas Engineering Association. He became chief engineer in 1940, manager of the Production Dept. in 1945, and a director of the company in 1948. Schilthuis has had 25 years' service with Humble and was made an assistant manager of the Production Dept. last year. The superintendent of Humble's gas division served as assistant head of the production division of the Petroleum Administration for War from 1941 to 1945.

☆

RAYMOND V. CRUCE has joined the firm of Robert W. Harrison & Co., consulting petroleum and geologists of Houston. He resigned as chief of the reserves group, Houston Div., of the Gulf Oil Corp., to accept this position.

☆

C. ARLISS WATTS has resigned his engineering position with A. O. Phillips, independent oil operator, to enter the petroleum consulting field in Corpus Christi, Tex. Watts, a petroleum engineering graduate from the University of Oklahoma, was associated with Phillips for two years and prior to that was with Shell Oil Co. for six years.

☆

FRED L. HOIPKEMEIER is now production engineer for Texkan Oil Co. of Dallas. He formerly was junior petroleum engineer for Stanolind Oil & Gas Co. in Wink, Tex. For a year and one-half following graduation in 1948 from the University of Oklahoma, he was with Halliburton Oil Well Cementing Co. Then he joined Stanolind and has been with them until this recent change.

WAYNE L. MCCANN and R. Lee Rogers, Jr., of Shreveport have associated as partners in a petroleum consulting firm. Offices of McCann and Rogers are located in the Petroleum Building. McCann, a registered petroleum engineer, has been a consultant since 1953, formerly having served as district engineer for Stanolind in Shreveport. Rogers, a geology graduate, was formerly with Stanolind and is now resigning as district geologist for the Murphy Corp. to form the partnership with McCann.

☆

HARRY DERNICK is vice-president of the newly-formed Production Management Inc., Denver. The firm will offer complete property management and engineering services for natural gas and oil producing properties in the Rocky Mountain area, Denver-Julesburg, and Canada. Dernick was formerly district engineer, chief primary engineer, and later assistant chief engineer in charge of oil and gas engineering and evaluation for Deep Rock Oil Corp. The University of Oklahoma petroleum engineering graduate has also worked for Republic Natural Gas Co. and Conroe Drilling Co.

☆

WILLIAM R. WAAG has accepted the position of petroleum engineer with The First National City Bank of New York. Prior to making this change, he was a senior engineer with Sohio Petroleum Co., in Oklahoma City. Before that, he was associated with Plymouth Oil Co., Sinton, Tex. He is a petroleum and natural gas engineering graduate of Pennsylvania State University.

BUCK J. MILLER opened an office in Wichita Falls on July 1 as a consulting petroleum and geological engineer. He received his BS degree from Texas A&M in 1941 and was first employed by The Texas Co. He continued with this company until 1952, his service being interrupted by a four year tour of duty in the U.S. Army Corps of Engineers. Then he resigned the position of district engineer of the Texas Co. in Wichita Falls area to join the staff of Russell Maguire, Oil Producer, as geological engineer, the position he held until opening his consulting office. He is currently serving as program committeeman for the North Texas Local Section.

☆

WILLIAM H. DAVISON is president and KENNETH DAVISON, vice president of the recently-formed Tekoil Corp. of Robinson, Ill. The company is the successor of Davison Co., and is a petroleum engineering and producing firm specializing in secondary recovery of oil. ROBERT L. SHICK, former engineer of water flooding for the Sohio Petroleum Co., heads the Tekoil Engineering Dept. Common stock in the company was recently offered for sale.

☆

EARL J. DAVIS has moved to the new sales office of Dowell Incorporated located at Carmi, Ill. The district area manager is a University of Oklahoma graduate and has been with Dowell since 1948. He has been area manager at Salem, Ill., since Nov., 1953. Prior to that he was a service engineer in Kansas and for two years was sales engineer in the company's general offices at Tulsa.

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EMPLOYMENT NOTICES

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, Address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 800 Fidelity Union Bldg., Dallas 1. These replies will be forwarded unopened and no fees are involved.

PERSONNEL AVAILABLE

☆ Petroleum Engineer, 27, desires position with independent or small company. Three years' experience in drilling, completion work, testing, workovers, and general production work with major company. Code 251.

☆ Petroleum Engineer, 33, with five years' experience in production and reservoir engineering seeks position with independent in Southwest area. Now employed by major company, married, one child. Code 252.

☆ Reservoir Evaluation Engineer, 36, desires position with independent, evaluation firm, or bank. BS degree in petroleum engineering. Seven years' experience in office work; two years' in field work. Now employed as reservoir evaluation engineer for major company. Single. Code 253.

☆ Petroleum and Geological Engineer desires a change in positions. Recent graduate with summer experience in oilfield work during school vacation. Now engaged in waterflooding work. Married. Code 254.

☆ Reservoir Engineer, 31, married, two years' general production and field experience, four years' reservoir engineering experience—principally flooding. Master's degree. Desires more varied oil industry experience with major or substantial independent. Present position supervisory reservoir engineer with $8,500 salary. Code 255.

☆ Petroleum Engineer with six years' intensive experience in Arkansas, Louisiana, and Texas, desires position with opportunity for advancement. Graduate of 1949, married, two children. Now employed, and responsible for drilling, workovers, production, and waterflood project for independent. Code 256.

☆ Petroleum Engineer, 26, completing military service obligation soon. Two years' experience in supervision of drilling, completion, workovers, and general production engineering. Desires position with small company. Now stationed in Houston. Married, one child. Code 248.

☆ Graduate Petroleum Engineer, age 32, married. Ten years' extensive experience in rotary and cable tool drilling, primary and secondary recovery production techniques, and administrative work for major and independent firms. Desires a responsible position anywhere in Continental North America with an aggressive organization. All offers acknowledged. Code 257.

☆ Registered Chemical Engineer, 43, married, two children. Ten years in drilling mud and fluid flow research. Background of physical metallurgy and physical and non-destructive testing and inspection. Looking for an opportunity to combine oilfield, research, and metallurgical experience. West Coast preferred. Now employed. Code 258.

☆ Experienced waterflood engineer capable of evaluating, developing, and managing flood properties desires position with aggressive independent. Has Oklahoma professional engineer registration. Code 259.

☆ Petroleum Engineer with five years' experience as construction and production engineer seeks position with small company, independent, or service company. Now employed by major company. Will locate anywhere, 29, married, veteran, two children. Code 260.

☆ Reservoir Engineer and Logging Expert, 35, married, with seven years' experience in field engineering and all phases of reservoir engineering with one major company. Currently employed as reservoir engineer in a key position. Desires responsible staff position with opportunity for advancement. Code 261.

POSITIONS OPEN

☆ Young man as full-time or part-time laboratory services supervisor. High school education with one or two years of college and business experience. Opportunity to take college courses. Basic salary—$242 per month. Write: Chairman, Dept. of Petroleum Engineering, The University of Texas, Austin.

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☆ Research mathematician or theoretical physicist. Major oil company research laboratory has opening for PhD or MS in the field of reservoir engineering research. Previous experience in applied mathematical research desirable but not necessary. Excellent working environment with opportunities for advancement. Replies confidential. Send detailed education and experience record, age, and state salary expected. Code 590.

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Shearman New Secretary of AIME Metals Branch

The new man behind the work-laden desk of the Metals Branch secretary is Robert William Shearman. He thus assumes the role left vacant by the promotion of Ernest O. Kirkendall to secretary of the Institute.

The son of mining engineer, Shearman is a 1937 graduate in chemistry from Princeton University. Graduate courses at Polytechnic Institute of Brooklyn, Pennsylvania State University Extension, Harvard University, Columbia University, and New York Institute of Finance filled in additional background in economics, metallurgy, and chemistry.

Following two years with Pittsburgh Plate Glass Co., he was employed by Bethlehem Steel Co. as a metallurgical observer, working in the open hearth and electric furnace shops. From 1946 to 1951 Shearman was with Union Carbide and Carbon Corp.

In 1951 he was recalled to the U. S. Air Force, but returned to Union Carbide in 1953 to become supervisor and later assistant division manager of the General Activities Div. of the General Publicity Dept.

Before joining the AIME staff Shearman was with Opinion Builders, Inc., a New York City public relations firm, where he specialized in technical publicity.

A number of technical and non-technical articles over his byline have appeared in newspapers, magazines, and journals. Married in 1954 to the former Dorothy French Dodge of Mountain Lakes, N. J., Shearman makes his home at 2 Stuyvesant Oval, New York City.

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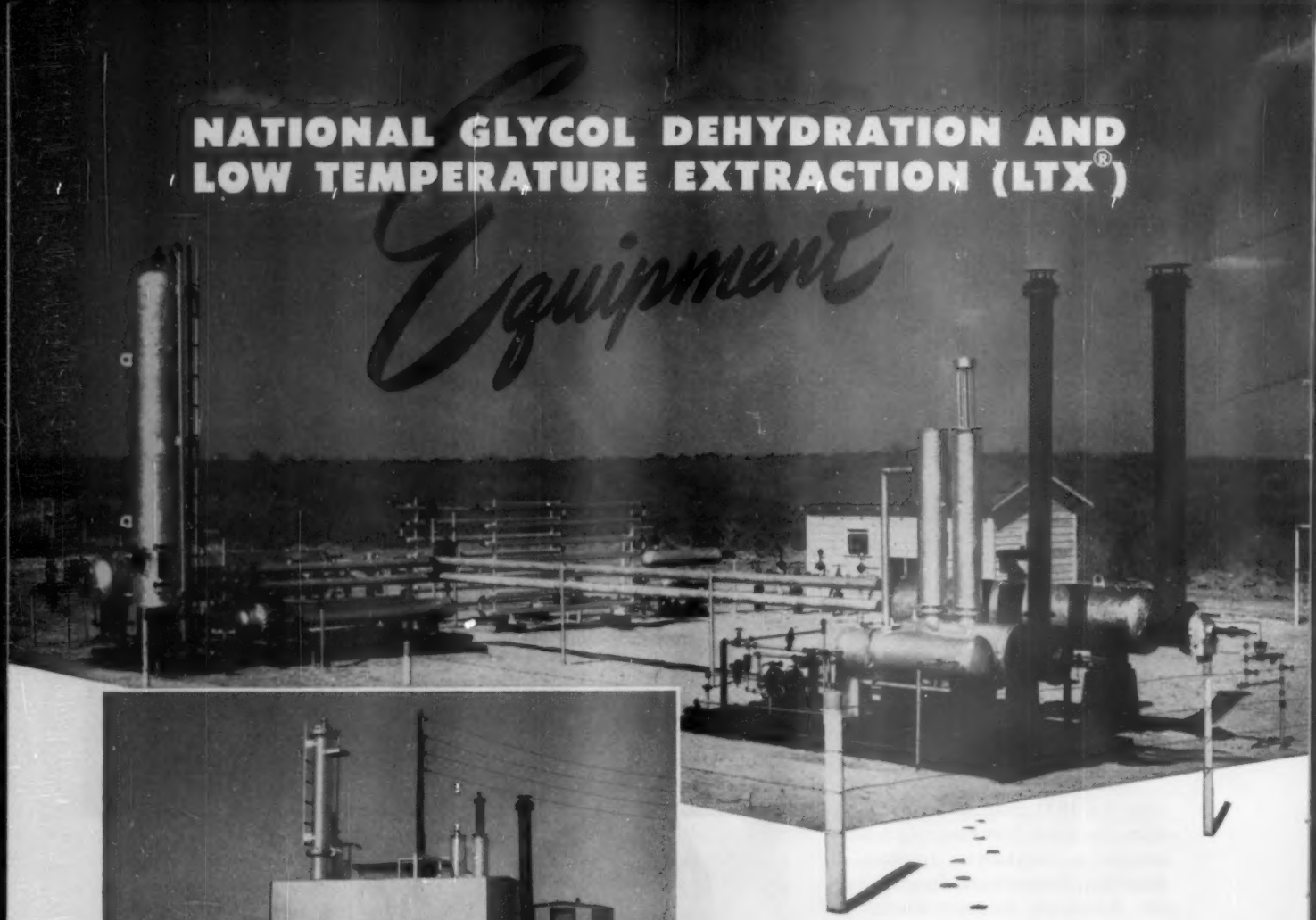

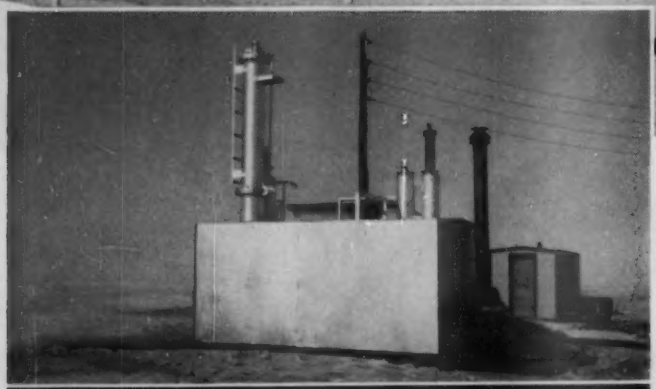

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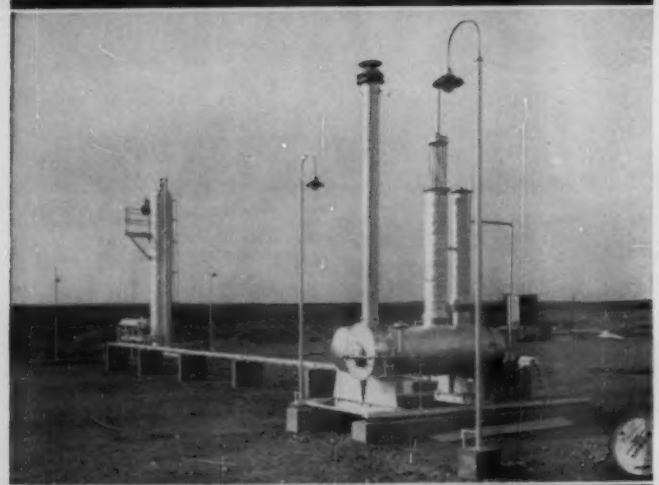

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A STUDY of ELECTRIC LOG INTERPRETATION METHODS in SHALY FORMATIONS

LEENDERT DE WITTE* | CONTINENTAL OIL CO.
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ABSTRACT

A review is given of the principles on which recently proposed methods of electric log interpretation in shaly sands are based and of the evidence brought up in support of the theoretical derivations. It is pointed out that the qualitative techniques suggested to date have a tendency to be too pessimistic in the prediction of the presence of commercial hydrocarbon accumulations.

In the quantitative treatment, a new concept is introduced, namely that of strongly reduced activity of the double layer counter ions which are present near the negatively charged rock surfaces. This lemma when applied to the calculation of the equilibrium concentrations of interstitial waters yields a set of very simple relations. The resulting expressions for electrochemical potentials across rock samples appear in satisfactory agreement with laboratory experiments. The formulae obtained for the electrical conductivity of shaly formations are of the same form as those arrived at empirically by previous workers. Combination of the expressions for potentials and conductivities gives a direct proof of the Tixier relation which states that for shaly water sands the product of apparent formation water resistivity and apparent formation factor equals the resistivity of the sand 100 per cent saturated with formation water and which was verified by the work of Wyllie and Perkins and their co-workers.

The relations for the resistivities and spontaneous potentials have been extended to the case of hydrocarbon bearing shaly formations, thus laying a formal basis for the quantitative interpretation of electric logs in shaly oil sands.

INTRODUCTION

The presence of disseminated clays in porous rocks saturated with electrolytic solutions has a strong influence on the transference of ions taking place under electrical or chemical potential gradients. Both the electrochemical emf's in evidence on the *SP* curves of electric logs and the electrical conductivity measured on resistivity logs are directly dependent on the ionic transference in the interstitial waters of the formations traversed by boreholes.

A large number of researches have been carried out on the nature and magnitude of the effects of clays on ionic transference. The most recent of these have been described in papers by McCardell and Winsauer,[1,2] Wyllie and Southwick,[3] Poupon, Loy, and Tixier,[4] and by Perkins et al.[5]

Most of these authors consider the effects of the clays as due to the fixed negative charges on the clay lattice. These charges cause the formation of diffuse surface layers with a high concentration of positive ions. The internal solution of the shaly reservoir rock has therefore a different ionic composition and concentration than the electrolyte with which it is in equilibrium (connate water produced from the formation or mud filtrate by which the formation is invaded). To calculate the equilibrium concentration of the internal solution, use is made of the Donnan[6] relation, which states that the mean ionic activities of the internal solution and of the external electrolyte must be equal. From this and the

*Author is now a petroleum consultant at Laguna Beach, Calif.

Paper presented at Petroleum Branch Fall Meeting in San Antonio, Oct. 17-20, 1954. Revised manuscript received in Petroleum Branch office on May 23, 1955.

Discussion of this and all following technical papers is invited. Discussion in writing (3 copies) may be sent to the offices of the Journal of Petroleum Technology. Any discussion offered after Dec. 31, 1955, should be in the form of a new paper.

[1]References given at end of paper.

fact that the internal solution must be electrically neutral (the total number of positive charges must equal the total number of negative charges), relations are derived for the internal concentrations which for the case of NaCl solutions take the form:

$$m_{c_l} \equiv m_X = -m_{R/2} + 1/2(m_R^2 + 4a_{AX}^2/\gamma_{AX}^2)^{1/2}$$
$$m_{Na} \equiv m_A = m_{R/2} + 1/2(m_R^2 + 4a_{AX}^2/\gamma_{AX}^2)^{1/2} \quad (1)$$

where m_{c_l} and m_{Na} are the chlorine and sodium concentrations in gram equivalents per 1,000 gm of solvent, m_R is the concentration of the fixed negative charges, a_{AX} is the mean ionic activity and γ_{AX} is the mean activity coefficient in the internal solution.

If a liquid junction is established within the reservoir rock between two solutions of different concentrations, an electrochemical emf will be formed across this junction. Treating the emf across an ion exchange membrane as the combination of two phase boundary potentials (at the boundaries between the external and internal solutions) and a diffusion potential between the two internal solutions, while assuming all activity coefficients to be equal to unity, Meyer and Sievers[7] and Teorell[8] derived a quantitative expression for the total electromotive force. This expression is commonly referred to as the Meyer-Sievers equation and is of the form:

$$E = \frac{RT}{F}\left[C\,ln\frac{2(m_A)_2 + (C\text{-}1)m_R}{2(m_A)_1 + (C\text{-}1)m_R} + 1/2\,ln\frac{(m_A)_1\,(m_X)_2}{(m_X)_1\,(m_A)_2}\right] \text{ where } C = \frac{u/v - 1}{u/v + 1} \quad . \quad . \quad (2)$$

u/v = mobility ratio of positive and negative ions in the internal solution, R = gas constant, F = Faraday, T = temperature (°K).

The conductivity of a shaly reservoir rock will be equal to a constant (the inverse of the formation resistivity factor) times the conductivity of the internal solution. The latter is given by:

$$\lambda = 96.5\,(n_A\,u + n_X\,v) \text{ mhos/cm} \quad . \quad . \quad (3)$$

where n_A and n_X are the concentrations of positive and negative ions in the internal solution, expressed in gram equivalents per liter of solution.

QUALITATIVE INTERPRETATION

Relations equivalent to Equations 2 and 3 form the basis for derivations by Perkins et al[5] leading to a qualitative method of electric log interpretation in shaly sands. This method expresses the log interpretation problem in shaly sands in terms of the parameters used in the analysis of clean formations. For clean water sands the following relations hold with reasonable accuracy:

$$(SP)_s = \frac{RT}{F}(1 - \frac{u - v}{u + v})ln\frac{R_{mf}}{R_w}.$$

$$(\approx 70 \log \frac{R_{mf}}{R_w} \text{ at } 77° \text{ F}) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$\text{and } F = \frac{R_i}{R_{mf}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where $(SP)_s$ is the static SP, R_{mf} and R_w are the resistivities of the mud filtrate and the formation water respectively, F is the formation (resistivity) factor and R_i is the resistivity of the mud filtrate invaded zone.

In shaly sands, the static SP is reduced by the presence of disseminated clays, and if we apply Equation 4 regardless of this fact, we obtain an apparent water resistivity $(R_w)_a$ which is larger than the actual water resistivity. The clay effect will also tend to reduce the magnitude of R_i; and if we apply Equation 5 to a shaly sand, we obtain an apparent formation factor, F_a, which is smaller than F.

Tixier has suggested that it is reasonable to assume that $F_a(R_w)_a = FR_w = R_o \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$ where R_o is the resistivity of the formation, 100 per cent saturated with water of resistivity R_w. Poupon, Loy, and Tixier[4] present evidence of field measurements in support of this rule. In the paper by Perkins et al[5] derivations are given which, by manipulation of relations equivalent to Equations 2 and 3 and by dropping a number of the smaller terms, end up with an expression for the SP in shaly sands of the form:

$$(SP)_s = 70 \log \frac{R_{xo}}{R_o} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6a)$$

which since $R_{xo} = F_a\,R_{mf}$ and $(SP)_s = 70 \log \frac{R_{mf}}{(R_w)_a}$ is equivalent to Equation 6. In addition the paper presents experimental evidence of the fact that Equation 6 holds true with sufficient accuracy for shaly water saturated core samples.

Wyllie and Southwick[3] present a number of measurements on both natural and artificially prepared shaly samples, to support the validity of Equation 6a for the case of 100 per cent water saturation.

For purposes of qualitative interpretation of logs in shaly sands it is suggested that the value of R_o computed in the above fashion be compared with the true formation resistivity, R_t. If R_t is appreciably larger than the computed R_o, the sand is oil or gas bearing; while if R_t is close to R_o, the formation contains mostly water.

It must be remembered, however, that all experimental evidence presented in support of Equation 6 is based on studies of water saturated samples.

If we apply Equation 6 to an oil bearing horizon, two new factors will simultaneously occur. First of all in an oil bearing shaly sand, the value of m_R will be increased (since the amount of water in the pore space is decreased, the concentration of the fixed charges in the interstitial water will be larger). The value of the static SP will be lower than when the same formation had been water bearing. Accordingly the value of $(R_w)_a$ will be larger than in the case of a water sand. Secondly, the invaded zone will contain a certain amount of residual oil which will cause R_i to be higher and F_a to be correspondingly larger than the F_a one would have found were the invaded zone completely saturated with mud filtrate. The effects of this second factor were pointed out by Wyllie and Southwick.[3]

If we now apply Equation 6, we find that both $(R_w)_a$ and F_a are too large and therefore the computed R_o will be an apparent R_o much larger than the resistivity of the formation 100 per cent saturated with water of resistivity R_w.

The apparent R_o may have a value quite close to that of R_t and the sand will be interpreted as containing mostly water. The suggested interpretation method will, therefore in general, give results which are too pessimistic and may lead to the by-passing of commercial accumulations of oil.

SCHLUMBERGER METHOD OF QUANTITATIVE ANALYSIS

To avoid the hazards involved in the qualitative interpretation, Poupon, Loy, and Tixier developed extensions

of Equation 6 to apply to partially oil or gas saturated sands. These equations are based on earlier work by Doll[9] on systems containing laminated clays and by de Witte[10] on resistivities of reservoir rocks containing dispersed clays. The new relations for formations with disseminated clays take the form:

$$\left(\frac{S_x}{S_{xo}}\right)^2 = \frac{F_x R_{wa}}{R_t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where S_x and S_{xo} are the fractions of total void space occupied by the conductive mixture of clays and water in the undisturbed formation and the invaded zone respectively. A somewhat similar equation is derived for the case of sands with laminated clay layers.

Bearing in mind the Archie relation for clean sands ($S_w^2 = \frac{R_o}{R_t}$), a comparison of Equations 6 and 7 shows that Equation 7 introduces a correction for residual oil present in the invaded zone and possibly a simultaneous adjustment for the effects of oil saturation on the *SP* deflection.

The equations for laminated shaly sands have been combined into an interpretation nomograph[4] which requires knowledge of the connate water resistivity R_w, along with the measured values of R_{xo}, R_t, and the *SP* deflection in order to determine the water saturation of a shaly sand. This additional requirement for the quantitative interpretation of shaly sands should be expected if we consider the facts that the inherent resolution of electric logs in shaly sands is smaller than in clean sands and that an additional unknown, namely the degree of shaliness of the sands, has to be taken into account.

Historically the Schlumberger method is of interest in that it combines the factors evolved from electrochemical considerations which yielded Equation 6 with the result of earlier physical model representations of the electrical behavior in shaly sands.

In the following an attempt will be made to compare this method with conclusions drawn from purely electrochemical derivations for the interpretation of oil bearing shaly sands.

ELECTROCHEMICAL RELATIONS IN SHALY FORMATIONS

Spontaneous Potentials

Instead of analyzing the shale membrane potentials in terms of the sum of phase boundary and diffusion potentials, one can simply consider the energy changes involved in the transference of ions through the membrane due to the chemical potential gradient and equate these to the equilibrium emf. This approach used by Scatchard[11] leads to the equation:

$$E = -\int_{\alpha}^{\omega} \Sigma_i\, t_i\, d\ln a_i \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where the transference number t_i is the number of moles of species i transferred in the direction of positive current for 1 Faraday passing through the system (this definition permits the use of transference numbers of neutral species, e. g. water). The term a_i is the activity of species i. Terms α and ω are the compositions of the solutions at each end of the system.

For the case of a solution of monovalent ions, we have:

$$\Sigma_i\, t_i\, d\ln a_i = t_A\, d\ln a_A + t_X\, d\ln a_X + t_w\, d\ln a_w = d\ln a_A + t_X\, d\ln a_A a_X + t_w\, d\ln a_w \quad . \quad (9)$$

(since $t_A - t_X = 1$); t_w denotes the transference number of the water.

Using Onsager's reciprocal relations, Staverman[12] showed that in calculating membrane potentials by equations of the form of Equation 8, we can omit the term for solvent transference, if we use the uncorrected Hittorf transference numbers $(t_X)_H$ and $(t_A)_H$ instead of t_X and t_A. This means that if in Equation 8 we express all transference numbers with respect to the solvent (which makes $t_w = 0$), we are correctly taking into account the effect of solvent transference on the membrane potentials. The uncorrected Hittorf transference numbers may be interpreted as the portions of total current carried by each species i. Equation 9 may now be written as:

$$\Sigma_i\, (t_i)_H\, d\ln a_i = d\ln a_A + (t_X)_H\, d\ln a_A a_X = d\ln a_A + (t_X)_H\, d\ln a^2_{AX} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Upon substitution of Equation 10 in Equation 8 the term $d\ln a_A$ integrates to $\ln (a_A)_\omega - \ln (a_A)_\alpha$. This is equal to the potential obtained across a perfect shale membrane, so that $\int_\alpha^\omega (t_X)_H\, d\ln a^2_{AX}$ represents the *SP* kick of a shaly sand measured with respect to the base line of a dense argillaceous shale. When measuring potentials across a core sample in the laboratory, we have to take both terms into account.

If by convention we take both the mobilities and the transference numbers of the anions as negative, we can write:

$$(t_X)_H = \frac{(u_X)_H\, m_X}{(u_A)_H\, m_A - (u_X)_H\, m_X}$$

Furthermore the electrical neutrality of the internal solution requires that $m_A = m_X + m_H$

Using the above expressions, Equation 10 gives:

$$\Sigma_i\, (t_i)_H\, d\ln a_i = d\ln a_A + \frac{(u_X)_H\, m_X}{(u_A)_H\, m_H + [(u_A)_H - (u_X)_H] m_X}\, d\ln a^2_{AX}$$

and the potential is given by:

$$E = \int_\alpha^\omega d\ln a_A + \int_\alpha^\omega \frac{\left(\frac{u_X}{u_A}\right)_H m_X}{m_H + \left[1 - \left(\frac{u_X}{u_A}\right)_H\right] m_X}\, d\ln a^2_{AX} \quad (11)$$

where according to Equation 1: $m_X = -m_{R/2} + 1/2\,(m_R^2 + 4\,a^3_{AX}/\gamma^3_{AX})^{1/2}$

Equations 8 through 11 are all given in units of $\frac{RT}{F}$.

Expressed in millivolts Equation 11 becomes (for 25° C or $T = 298°K$)

$$E = 59.1 \int_\alpha^\omega d\log a_A + 118.2 \int_\alpha^\omega \frac{\left(\frac{u_X}{u_A}\right)_H m_X}{m_H + \left[1 - \left(\frac{u_X}{u_A}\right)_H\right] m_X}\, d\log a_{AX} \quad . \quad . \quad . \quad (12)$$

It can be shown that Equation 12, with m_X given by Equation 1, is basically the same as the Meyers-Sievers equation except that the effects of the solvent transference have been taken into account.

The Meyer-Sievers equation is usually evaluated assuming $\frac{u_X}{u_A}$ to be the same as in free solutions and taking γ_{AX} equal to unity. A slight refinement can be made by taking both the mobility ratio and the mean

activity coefficient for the internal solution as equal to those for free solutions of the same average concentration. Fig. 1 shows a plot of emf's calculated from Equation 12 using these latter assumptions for constant ratio of ω over α ($\omega = 4\alpha$) and various values of m_R. The calculated emf's are plotted against $1/\alpha$. We notice that these curves predict that for dilute solutions ($\alpha < 0.01$) the membranes behave very nearly as perfect cation exchangers even for very small values of m_R.

Fig. 2 shows a similar plot obtained by laboratory measurements on a series of core samples ranging from dense black shale to very nearly clean sands. Comparison with Fig. 1 shows appreciable discrepancies between the experimental emf's and their theoretically predicted values, especially for the more dilute solutions. The experimental family of curves shows a good internal consistency suggesting some conceptional inaccuracy in the theory rather than experimental errors as the cause of the discrepancies. The data represented in Fig. 3 of the paper by Wyllie and Southwick[3] show the same shortcomings of the Meyer-Sievers equations as applied to dirty sands.

It is natural to expect that the weak points of the theoretical predictions lie in the assumptions made regarding the mobility ratio's $\left[\frac{u_X}{u_A}\right]_H$ and the activity coefficient, γ_{AX}, in the internal solution. The former have a marked influence on the values of the computed emf's for concentrated solutions, as was shown in the original work by Meyer and Sievers. As observed by these authors, factors such as pore size distribution of the membranes may cause the apparent mobility ratio in the membrane to differ from that in free solutions. By adjustment of the assumed mobility ratio, it is easy to bring the computed emf's for the concentrated solutions in agreement with the experimentally observed values.

For dilute solutions, however, the effect of variations in mobility ratio on the emf's becomes very small and quite insufficient to explain the discrepancies between the curves of Figs. 1 and 2.

The theoretical curves shown in Fig. 1 and the Meyer-Sievers relations both are based on values for the concentration of the internal solution given by Equation 1. It appears to be in order to critically re-

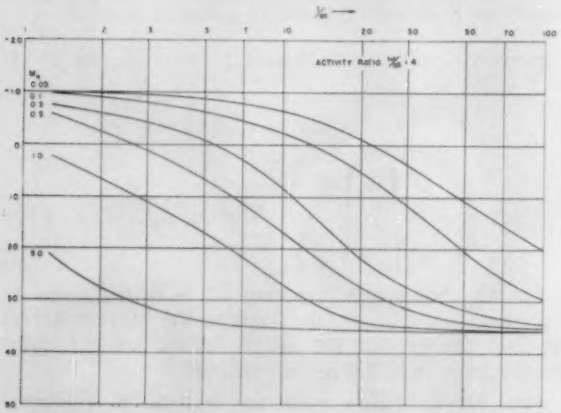

FIG. 1 — MEMBRANE POTENTIALS CALCULATED FROM EQUATION 12. (WITH ACTIVITIES OF INTERNAL SOLUTION EQUAL TO THOSE OF FREE SOLUTIONS OF SAME CONCENTRATION)

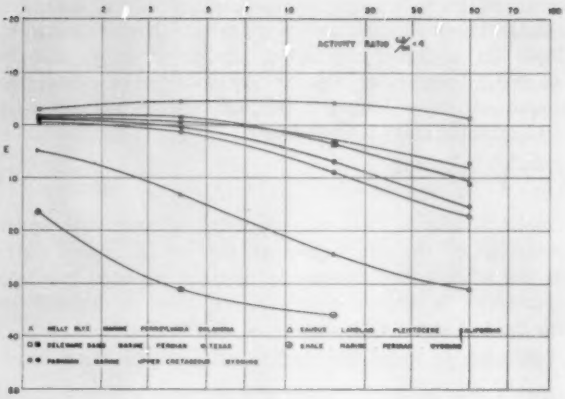

FIG. 2 — MEASURED POTENTIALS ACROSS VARIETY OF CORE SAMPLES.

examine the origin of this equation. As stated before Equation 1 is derived using the condition of electrical neutrality and the Donnan equilibrium relation. The derivations in the original work by Donnan[6] were made for the case of ideal solutes and a completely homogeneous dispersion of the fixed charges (non-mobile ions) in the electrolytic solution. The corresponding equilibrium relation is given in terms of concentrations and for NaCl solutions would take the form $m_{Na} \cdot m_{Cl} = m'_{Na} \cdot m'_{Cl}$. This leads directly to the expressions in Equation 1 for the case of $\gamma_{AX} = 1$ and to the corresponding form of the Meyer-Sievers equations. McCardell et al[5] showed that the Meyer-Sievers relation may also be derived from the Boltzmann distribution function, again using the assumption of homogeneous dispersion of the fixed charges and ideal behavior of the solutes.

As a first correction for the non-ideal behavior of the ions, activities are substituted for concentrations. This correction attempts to take into account the effects of ionic interaction and the resulting decrease of the degree of randomness in the ionic distribution. Each positive ion is surrounded by a slightly larger number of negative ions than positive ions and vice versa. Each ion moves therefore in the electrical field of its surrounding ion cloud, and its activity is decreased in proportion to the strength of this electrical field. The activity coefficient is used to indicate the extent by which the activity has decreased from that

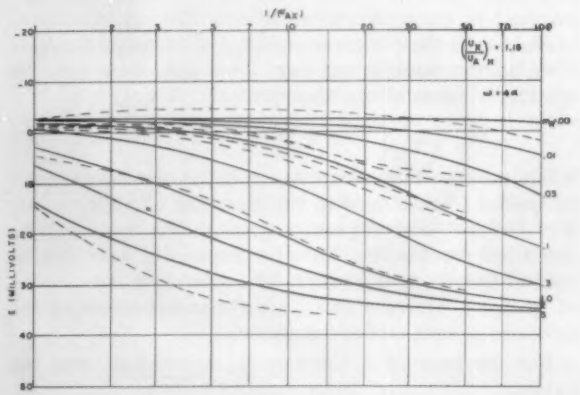

FIG. 3 — POTENTIALS CALCULATED ASSUMING NEGLIGIBLE ACTIVITY OF COUNTER-IONS (EQUATION 16). DASHED LINES INDICATE MEASURED VALUES OF FIG. 2.

of an ideal solution. In fairly concentrated solutions the activity coefficients may be of the order of 0.5. Considering now the actual composition of the internal solution of a shaly sand, we know that the fixed charges are not homogeneously distributed throughout the solution, but are concentrated on the surfaces of the clay particles. The charged surfaces attract a high concentration of positive ions as diffuse layers of counter ions. This arrangement has a highly marked lack of randomness and has consequently a pronounced electrical field. The activity coefficient of the positive counter ions in these electrical fields are correspondingly strongly reduced.

This conclusion leads to the following formulation of the Donnan equilibrium for the case of shaly formations:

$$m_X \gamma_X (m_X \gamma_X + m_R r \gamma_X) = a_{AX}^2 \text{ or}$$

$$\gamma_X^2 (m_X^2 + r\, m_R\, m_X) = a_{AX}^2 \quad . \quad (13)$$

where r is the factor by which the activity of the positive double layer ions is reduced compared to the remainder of the ions in the internal solution. Solving Equation 13 for m_X we obtain:

$$m_X = -\frac{r m_R}{2} + \tfrac{1}{2}\left[(r m_R)^2 + 4 a_{AX}^2/\gamma_X^2\right]^{1/2} \quad . \quad (14)$$

A rigorous calculation of typical values of r is beyond the scope of this paper. A value of r equal to 0.1 or smaller seems however quite plausible. It can further be shown that reduction factors much smaller than 0.1 give only slight additional effects on the calculated emf's beyond those obtained for $r = 0.1$, so that the assumption $r = 0.1$ is nearly equivalent to omitting the terms $r\, m_r$ completely in the expression for m_x. The latter step gives:

$$m_x = \frac{a_{AX}}{\gamma_X}$$

and with γ_X taken equal to the mean activity coefficient in free solutions of concentration m_X we find that m_X is equal to the concentration of the external solution. Equation 12 therefore reduces to:

$$E = 59.1 \int_a^{\omega} d \log a_A + 118.2 \int_a^{\omega} \frac{\left(\frac{u_X}{u_A}\right)_H m}{m_R + \left[1 - \left(\frac{u_X}{u_A}\right)_H\right] m} d \log a_{AX} \quad . \quad (15)$$

where m is found for each value of a_{AX} from the known relations between activity and molality of free solutions.

The experimental emf's of Fig. 2 for very concentrated solutions indicate a change in the value of $\left(\frac{u_X}{u_A}\right)_H$ due to the pore structure. A value of $\left(\frac{u_X}{u_A}\right)_H \approx -1.15$ is suggested. With $\left(\frac{u_X}{u_A}\right)_H = -1.15$, Equation 15 becomes:

$$E = 59.1 \int_a^{\omega} d \log a_A - 118.2 \int_a^{\omega} \frac{1.15m}{m_R + 2.15m} d \log a_{AX} \quad . \quad (16)$$

Fig. 3 shows a plot of E vs $1/\alpha$ calculated from Equation 16 for various values of m_R. The experimental curves of Fig. 2 are shown in this figure by dashed lines. The agreement of the two families of curves appears quite satisfactory.

The expression for the *SP* deflection measured from a shale base line now becomes:

$$(SP)_s = -118.2 \int_{a_{mf}}^{a_w} \frac{1.15m}{m_R + 2.15m} d \log a \quad . \quad (17)$$

where a_w and a_{mf} are the mean ionic activities of the connate water and the mud filtrate respectively. Approximating the mean activity by the molality m, Equation 17 can be formally integrated to:

$$(SP)_s = -59.1 \left[\frac{2 \times 1.15}{2.15} \log (m_R + 2.15m)\right]_{m_{mf}}^{m_w}$$

$$\text{or } (SP)_s = -63.3 \log \frac{m_R + 2.15\, m_w}{m_R + 2.15 m_{mf}} \quad . \quad (18)$$

If we do not wish to assign a specific value to $\left(\frac{u_X}{u_A}\right)_H$ or if we want to take its variation with temperature into account, we can obtain directly from Equation 15 the general expression:

$$(SP)_s = 59.1 \frac{2\left(\frac{u_X}{u_A}\right)_H}{1 - \left(\frac{u_X}{u_A}\right)_H} \log \frac{m_R + \left[1 - \left(\frac{u_X}{u_A}\right)_H\right] m_w}{m_R + \left[1 - \left(\frac{u_X}{u_A}\right)_H\right] m_{mf}} \quad . \quad (19)$$

If we choose to use a mobility ratio equal to that of free solutions, which is normally taken as $\left(\frac{u_X}{u_A}\right)_H = -1.5$, Equation 19 gives:

$$(SP)_s = -71 \log \frac{m_R + 2.5\, m_w}{m_R + 2.5\, m_{mf}} \quad . \quad (19a)$$

CONDUCTIVITY OF SHALY WATERSANDS

The electrical conductivity of a 100 per cent water saturated rock is given by:

$$C_o = \frac{1}{R_o} = \frac{\lambda}{F^*}$$

where λ is the conductivity of the internal solution and $1/F^*$ is the "cell constant" of the inert rock network.

The conductivity of the internal solution can be expressed as:

$$\lambda = 96.5\, (n_A\, u_A - n_X\, u_X)$$

where n_A and n_X are the concentrations of the positive and negative ions in gram equivalents per liter. If we denote the conversion factor of normality to molality of the electrolyte by β so that $\beta = \frac{n}{m}$ we have:

$$\lambda = 96.5\, \beta\, [u_A\, (m_R + m_X) - u_X\, m_X]$$

$$\text{or } \lambda = 96.5\, \beta\, [u_A\, m_R + m_X\, (u_A - u_X)] \quad . \quad (20$$

For the free solution with which the internal solution is in equilibrium we have similarly:

$$\lambda' = 96.5\, \beta\, m\, (u_A' - u_X')$$

and with $m_X = m$ we can write:

$$\lambda = a + b\, \lambda' \text{ where } a = 96.5\, \beta\, u_A m_R$$

$$\text{and } b = \frac{u_A - u_X}{u_A' - u_X'} = \frac{1 - u_X/u_A\, u_A}{1 - u_X'/u_A'\, u_A'}$$

The conductivity of the rock now becomes:

$$\frac{1}{R_o} = \frac{1}{F^*}(a + b\lambda') = \frac{1}{F^*}\left(a + \frac{b}{R_w}\right) \quad . \quad (21)$$

where a and b are constants depending on the shaliness and texture of the rock.

Equation 21 is of the same form as the relations found earlier by Patnode and Wyllie[10] and by de Witte.[11] The form of the equation is at variance with the data obtained by Wyllie and Southwick[3] in experiments on samples made up of cation exchange resin material (IR-120) and glass spheres. This apparent disagreement warrants further elucidation.

When experimentally testing the equations for the resistivity of water bearing shaly sands, the simplest criterion to apply is that according to Equation 21, a plot of $1/R_o$ vs $1/R_w$ must give a straight line.

Fig. 4 shows a number of such plots obtained from resistivity measurements on the same type of samples on which the electrochemical emf's were measured. The Saugus samples are so shaly that this facies of the formation cannot be considered as a commercial reservoir rock. The Nelly Blye is very close to a clean sandstone, while the Parkman and Delaware sands are intermediate in shaliness. In addition a plot of the data given in Table 2 of the paper by Wyllie and Southwick for the Stevens sandstone, is shown. It is noted that the straight line relation holds with sufficient accuracy for all these samples, down to water conductivities well below those encountered in practice. For comparison the data given by Wyllie and Southwick for the IR-120 spheres are plotted on the same scale as those for the shaly sands. The strong deviation from linearity of this plot is readily apparent.

Careful examination of the premises on which Equation 21 is based, and which appear to be satisfied for shaly sands, yields a simple explanation for the differing results of the IR-120 experiments. In Equation 3 from which Equation 21 was derived it is implied that the clay particles are sufficiently small and randomly enough distributed so that their double layer conductivity can be added directly to that of the remainder of the electrolyte in the pore spaces. For shaly sands with clay particle sizes of the order of microns or smaller and very random distribution of the clays in the void space this condition appears to be satisfied. For regularly packed spheres of IR-120 with an average diameter of around 400 microns, the condition is definitely not fulfilled and we actually have a well described geometry of two media of different conductivities. The resultant over-all conductivity for such cases is usually not a linear combination of the two component conductivities, as is shown in the analogous cases of mixtures of sand grains (zero conductivity) and electrolyte and mixtures of oil and electrolyte. The former gives the nonlinear porosity-formation factor relation while the latter is described by the nonlinear Archie equation.

In Fig. 6 of the paper by Wyllie and Southwick we also note that the IR-120 mixtures do not follow the Tixier relation, over part of the concentration range of practical interest while the data on the shaly sands shown in the same figure do obey this rule.

It is clear therefore that observations made on the aggregates of relatively large spheres of cation exchange resin cannot be used as criteria for the relations on which electric log interpretation methods in shaly sands may be based.

Since the conductivity of the internal solution cannot be measured independently and the cell constant F*, therefore, is difficult to evaluate, it is more practical to define the resistivity formation factor F as:

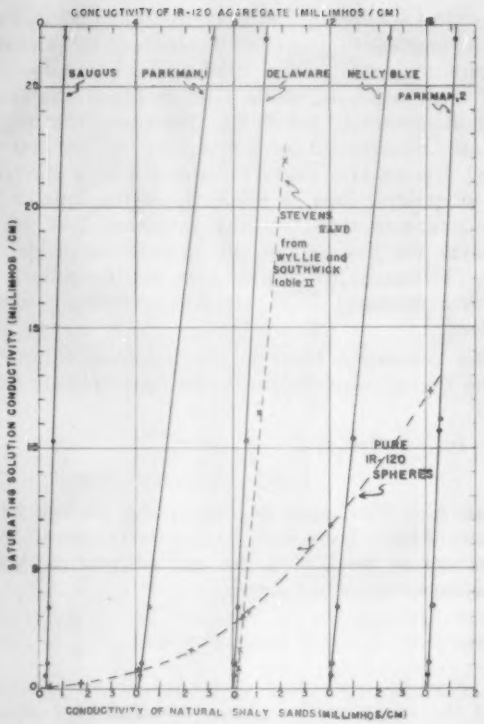

FIG. 4—COMPARISON OF CONDUCTIVITY RELATIONS FOR NATURAL SHALY SANDS AND "ARTIFICIAL SHALY SANDS."

$$F = \lim_{R_w \to 0} \left(\frac{R_o}{R_w}\right)$$

From Equation 21 $\frac{R_o}{R_w} = \frac{F^*}{aR_w + b}$ so that

$$F = \lim_{R_w \to 0} \left(\frac{R_o}{R_w}\right) = \frac{F^*}{b}$$

$$\text{and } \frac{1}{R_o} = \frac{1}{F}\left(\frac{a}{b} + \frac{1}{R_w}\right) \quad . \quad . \quad . \quad . \quad . \quad (20)$$

THE TIXIER RELATION

The relationship between the *SP* deflections and resistities in shaly sands can be easily derived from the foregoing equations. Using the value of $\frac{u_x}{u_\lambda} = -1.15$ in Equation 20 we have:

$$\lambda = 96.5\,\beta\,u_\lambda\,(m_R + 2.15m_x)$$

$$\text{and } R_o = \frac{F^*}{96.5\,\beta\,u_\lambda}\left[\frac{1}{m_R + 2.15m_x}\right]$$

Applying this expression to the invaded zone (with $m_x = m_{mf}$) and the undisturbed formation (with $m_x = m_w$) respectively and substituting the results in Equation 18 we obtain:

$$(SP)_s = -63.3 \log \frac{R_{xo}}{R_o} \quad . \quad . \quad . \quad . \quad . \quad (22)$$

Again if we choose to take the mobility ratio in the internal solution equal to that in free solutions the constant in the above expression for the static *SP* becomes 71 instead of 63.3, which shows close agreement with Tixier relation as given by Equation 6.

SP IN OIL BEARING FORMATIONS

If we replace part of the interstitial water of a formation by oil, while the pore surface remains water wet and the resulting water saturation expressed as a fraction of pore space is equal to S_w, the concentration of fixed negative charges in the internal solution is increased by a factor of $\frac{1}{S_w}$.

Similarly in the invaded zone the concentration of fixed charges becomes m_r/S_{wi}, where S_{wi} is the water saturation in the invaded zone. We can now distinguish two cases, dependent on the characteristics of the boundary between the invaded zone and the formation beyond this zone.

If we consider the salt content of the connate water to have partly diffused back into the invaded zone, we have the cell:

$$R_{mf} \;\Big|\; R_{mf};\, m_n/S_{wi} \;\Big|\; R_w;\, m_n/S_{wi} \;\Big|\; R_w;\, m_n/S_w$$

For this case the SP deflection will be given by:

$$(SP)_s = -K_c \log \frac{m_n/S_{wi} + 2.15m_w}{m_n/S_{wi} + 2.15m_{mf}}$$

On the other hand we might consider the internal solution of the undisturbed formation immediately beyond the invaded zone to be in equilibrium with the mud filtrate. This case may be represented by the cell:

$$R_{mf} \;\Big|\; R_{mf};\, m_n/S_{wi} \;\Big|\; R_{mf};\, m_n/S_w \;\Big|\; R_w;\, m_n/S_w$$

The SP deflection for this case will be:

$$(SP)_s = -K_c \log \frac{m_n/S_w + 2.15m_w}{m_n/S_w + 2.15m_{mf}} \quad . \quad (23)$$

Since m_n/S_w is larger than m_n/S_{wi}, salt diffusion through the invaded zone will be more rapid than in the undisturbed formation and this latter case will eventually prevail. Here $K_c \approx \frac{63.3}{298} T \approx 0.21\ T$, where T is the absolute temperature (°K).

RESISTIVITY OF OIL-BEARING FORMATIONS

The effects of oil saturation on the resistivity of shaly rocks consists essentially of two parts. First, the concentration of fixed charges in the internal solution is increased to m_n/S_w which changes the conductivity of the remaining interstitial water to:

$$\lambda = 96.5\ \beta\ u_A\ (m_n/S_w + 2.15m) \quad . \quad . \quad (24)$$

Secondly, the oil makes part of the pore space nonconductive and forces the current paths to become more tortuous. This latter effect has been treated earlier by de Witte[10] and is expressed by the relation:

$$\frac{1}{R} = \frac{1}{F'} \lambda S_w \text{ where } F' = \frac{F}{S_w} \text{ so that we obtain:}$$

$$\frac{1}{R} = \frac{\lambda}{F} S_w^2 = \frac{96.5\ \beta\ u_A}{F} (m_n/S_w + 2.15m)\ S_w^2 \quad (25)$$

Applying this to the undisturbed formation and to the invaded zone respectively we obtain:

$$\frac{1}{R_t} = \frac{C}{F} (m_n/S_w + 2.15m_w)\ S_w^2 \quad . \quad . \quad . \quad (26)$$

and $$\frac{1}{R_{xo}} = \frac{C}{F} (m_n/S_{wi} + 2.15m_{mf})\ S_{wi}^2$$

where R_{xo} and S_{wi} are the resistivity and the water saturation of the invaded zone and $C = 96.5\beta u_A$.

Equations 23 and 26 form the basis for the quantitative interpretation of shaly oil sands and may be combined by writing:

$$\frac{R_{xo}}{R_t} = \frac{(m_n/S_w + 2.15m_w)\ S_w^2}{(m_n/S_{wi} + 2.15m_{mf})\ S_{wi}^2} =$$

$$\frac{(m_n/S_w + 2.15m_w)}{(m_n/S_w + 2.15m_{mf})} \times \frac{S_w}{S_{wi}} \times \frac{m_n/S_w + 2.15m_{mf}}{m_n/S_w + 2.15S_{wi}/S_w\ m_{mf}}$$

Using Equation 23, we obtain after rearrangement:

$$(SP)_s = -K_c \left[\log \frac{R_{xo}}{R_t} + \log \frac{S_{wi}}{S_w} + \log \frac{m_n/S_w + 2.15S_{wi}/S_w m_{mf}}{m_n/S_w + 2.15m_{mf}} \right] \quad . \quad . \quad . \quad . \quad . \quad (27)$$

To use Equation 27 it is in general necessary to know the connate water resistivity. With knowledge of R_w or m_w, we can solve Equation 23 for the value of m_n/S_w and subsequently evaluate S_{wi}/S_w from Equation 27.

In the case of a wildcat well where R_w is not known but where the general character of the sand can be judged either from the log by comparison with neighboring formations or from the lithological description of drill cuttings, we can use the following approximations:

For relatively clean sands and saline muds ($m_n \ll m_{mf}$), Equation 27 reduces to:

$$(SP)_s = -K_c \left[\log \frac{R_{xo}}{R_t} + 2 \log \frac{S_{wi}}{S_w} \right] \quad . \quad (28)$$

This is similar to the expression given by Poupon et al for formations containing disseminated clays, except for the somewhat different interpretation of K_c and the fact that the ratio $\frac{S_{wi}}{S_w}$ replaces $\frac{S_{xo}}{S_x}$ where the quantities in the latter ratio denote the fractions of total void space occupied by the conductive mixture of water and clays.

For very shaly formations, and fresh mud ($m_n \gg m_{mf}$), we obtain:

$$(SP)_s = -K_c \left[\log \frac{R_{xo}}{R_t} + \log \frac{S_{wi}}{S_w} \right] \quad . \quad (29)$$

Where neither the character of the formation can be judged nor the value of R_w is known, Equations 28 and 29 will serve to give the limiting values of S_w/S_{wi}.

FIELD EXAMPLE

Fig. 5 shows a conventional electric log through an Oligocene sand section in South Louisiana. The zone analyzed is the center portion of the bed between 11,908 ft and 11,940 ft. The following data are pertinent: The hole diameter $d = 6$ in; $R_m = .51$ at 100° F $= .22$ at 216° F (formation temperature); $R_{mf} = .13$ at 216° F: $(SP)_s = 25\ mV$. From simplified departure curve analysis[14] using the two normal curves, in conjunction with the reading of the long lateral curve we find: $R_t/R_m = 8.0$; $R_t/R_m = 6.0$; $R_t/R_t = 1.33$; $R_t = 1.76$; and $R_t = 1.32$.

For the qualitative procedure using F_s $R_{wa} = R_o$, we have: $F_s = \frac{1.76}{.13} = 13.5$. To find R_{wa}, we must use the relation $(SP)_s = K \log \frac{R_{mf}}{R_{wa}}$, where K is the SP constant for clean sands which should equal approximately 85 at 216° F. This gives $25 = 85 \log \frac{.13}{R_{wa}}$ or $R_{wa} = .66$

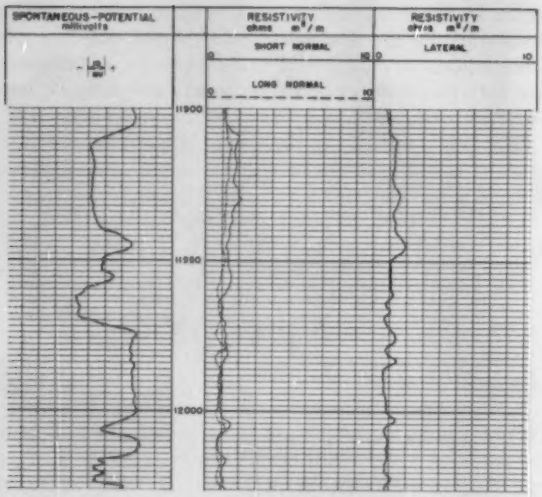

FIG. 5—CONVENTIONAL ELECTRIC LOG THROUGH SHALY SAND SECTION.

ohm-m. Finally $F_s R_{ws} = R_o = 13.5 \times .66 = .88$. When compared with the R_t value of 1.32, we obtain $R_t = 1.48\ R_o$. This ratio looks fairly unpromising and it might lead to serious doubts about the value of the sand in question as a potential oil horizon.

For the quantitative evaluation it can be ascertained from comparison with neighboring horizons (not shown in Fig. 5) that the sand is quite shaly, while the mud is not saline. Equation 29 should therefore apply with fair accuracy. Substituting the values of $(SP)_s$ and $\frac{R_{xo}}{R_t}$ given above (assuming $R_{xo} \approx R_t$) and using $K_t = 0.21T = 79$, we have:

$$25 = 79 \left[\log 1.33 + \log \frac{S_{wt}}{S_w} \right] \text{or} \frac{S_{wt}}{S_w} = 1.55$$

If we assume a residual oil saturation in the invaded zone of 30 per cent, we find $S_w = \frac{0.7}{1.55} = .45$. This means an oil saturation of 55 per cent.

The formation in question tested 323 BOPD and no water on ⅛ in choke through perforations at 11,908 ft to 11,920 ft.

CONCLUSIONS

Based on the concept of reduced ionic activity of the double layer counter ions near the negatively charged rock surfaces in shaly sands, a new set of electrochemical relations has been derived.

These relations yield simple expressions for the *SP* in shaly sands involving the concentration of fixed charges in the internal solution of the rock network as a general parameter, indicative of the degree of shaliness of the formation. Experimental evidence is given in support of the new equations.

Expressions derived for the conductivity of water-bearing shaly formations agree with the empirical equations found by earlier workers.

Further proof has been given of the Tixier relation equating the product of apparent formation factor and apparent connate water resistivity in water sands to R_w.

A set of equations is derived giving a formal basis for the quantitative interpretation of electric logs for shaly oil-bearing formations.

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TEMPERATURE SURVEYS in GAS PRODUCING WELLS

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ABSTRACT

A method for the interpretation of temperature curves recorded in gas producing wells is described. One essential feature of the method is a simple graphical construction which conveniently reflects the amount of gas flowing from a given producing formation.

This method, applied in conjunction with the Induction Log and radioactivity logs, is valuable to determine the points of entry of gas and to estimate the over-all thickness of the producing zones and their respective contributions to the total production. The method in particular is helpful in evaluating the effect of fracturing operations.

An outstanding result of the application of the method is to bring to the light the relative importance of sand-shale interfaces in the production of gas.

The paper is illustrated with field examples.

INTRODUCTION

The electrical logging tools involving conventional systems are not applied in wells which do not contain water base mud (empty holes, or wells filled with oil base mud), because of the absence of electrical connection between the electrodes and the surrounding formations. It is, therefore, common practice in this case to use other methods which do not require the presence of a conductive fluid in the borehole: resistivity log with scratcher electrodes, Induction Log, radioactivity logs, temperature log. . . .

Such conditions are encountered in some regions, as the San Juan Basin, N. Mex., where a technique of drilling gas wells, using gas as a drilling fluid, has been introduced in the last two years.

By the middle of 1953, an appropriate method for the logging of these wells was devised on the basis of field tests and of theoretical studies. It is the purpose of the present paper to give a description of this method.

In these wells the logging operations are performed during the process of gas production, so that the temperatures in the boreholes are strongly affected by the cooling due to the expansion of the gas. On the other hand, a special thermometer, with a high sensivity and a short time constant, has been recently made available, which has enabled much more detailed and accurate recordings of the borehole temperatures than with the conventional instruments. As a result of these two circumstances, the temperature log constitutes the essential element of the method, in making possible the detection of the gas producing zones, the definition of their boundaries, and the estimation of the respective contributions of each separate zone to the total production.

The method also involves the radioactivity and Induction Logs, as auxiliary documents. These logs in the present instance are helpful in the determination of the reservoirs. However, the information they give in this respect is limited. This comes from the fact that, due to the absence of the MicroLog and/or MicroLaterolog and of the *SP* log, the estimation of formation factors and connate water salinities is somewhat conjectural. Furthermore, little help is obtained from the Neutron log for the evaluation of porosity and of formation factor because the variations of gas saturation affect the Neutron log in a way similar to the variations of porosity.

It should be said also that even an exact knowledge of the gas saturation of the reservoir beds would not

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permit in general a correct estimation of their possible productions. This is because the formations encountered in those wells are consolidated with low permeabilities, and, as a rule, are artificially treated by shooting or hydraulic fracturing to stimulate the production.

In the following, the principles of the interpretation of the temperature logs will be explained first. Next, the practical applications of the temperature curves, combined with the other logs, will be discussed using actual field examples. Finally, an outline of the mathematical treatment of the problem will be given.

PRINCIPLES OF INTERPRETATION OF TEMPERATURE CURVES

Gas escaping from a high pressure producing bed into a dry hole undergoes a considerable cooling. This cool gas mixes eventually with warmer gas coming from below and produces a drop in the temperature log opposite a gas zone, which may attain 20° F or more* (see field examples). The amount of cooling is determined by several factors:

1. The radial distribution of pressure in the bed, which in turn depends on the permeability and porosity of the formation and the length of time the bed has been producing.
2. The thickness of the bed.
3. The thermal conductivity of the formation.
4. The amount of gas produced compared to the amount coming from below (for the case of a producing zone located above one or several other producing beds).

Determination of the Boundaries of the Gas Producing Zones

Determination of the boundaries of the gas producing zones is based on the knowledge of the shape of the temperature log at the various levels of the gas-producing zones. The shape of the curve is different according to whether the producing zone is the closest to the bottom of the hole or is located above.

Fig. 1 shows the typical shapes of the temperature log computed in the case of two beds which are supposed to produce about the same amount of gas, the lower bed being the first producing zone from the bottom. The graph traced on the figure should be considered as being somewhat schematic because several simplifying assumptions have been involved in the computation. The geothermal gradient, in particular, has been neglected and it has been assumed that all the cooling takes place substantially at the wall of the hole. It has been also supposed for the computation that there was no vertical heat exchange: in practice therefore the sharp breaks indicated on the theoretical curve will not be observed in actual surveys but will be rather rounded as shown qualitatively by the dashed line. Despite those approximations, the essential difference in shape between the lower and the upper bed is clearly indicated: at the level of the lower bed the temperature curve shows a plateau AB, A and B being located respectively at each boundary of the bed. At the level of the upper bed, a continuous decrease of temperature is observed from A' opposite the bottom boundary to B' opposite the top boundary.

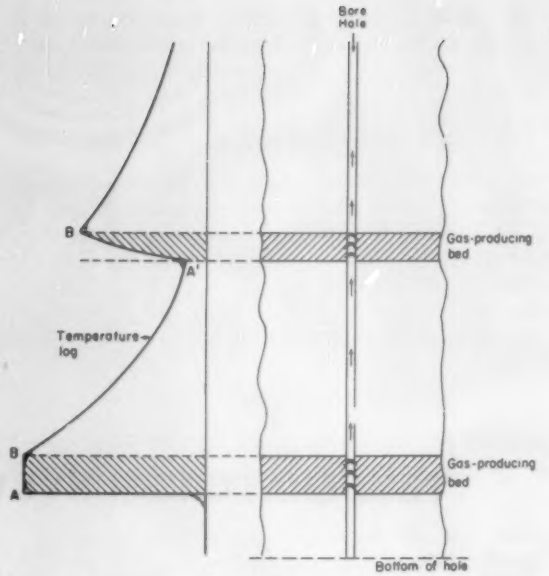


FIG. 1 — COMPARATIVE SHAPES OF THE TEMPERATURE LOG OPPOSITE A GAS-PRODUCING BED FIRST FROM BOTTOM OF HOLE, AND A GAS-PRODUCING BED LOCATED ABOVE. (DERIVED FROM APPROXIMATE COMPUTATIONS WITH GEOTHERMAL GRADIENT NEGLECTED.)

Temperature Curve Above a Producing Zone

It is supposed that the thermal conductivity of the formation above the bed is sensibly uniform, which seems to be the case in general, and that there is no other producing zone at a short distance above. The corresponding theoretical derivations will be given later on. Results of interest for the practical interpretation of the temperature logs are explained below (Fig. 2)**.

1. At the level of the producing bed, the gas undergoes cooling and, therefore, immediately above the bed it will be gaining heat from the formation; its temperature is lower than that of the formation. But at a great distance above the producing bed (assuming that there is no other gas zone or other temperature disturbance), the temperature T' of the formations remote from the wall has become so much lower, in conformity with the geothermal gradient, that now the gas will be losing heat to the formations. In between, there is some point I which will be called the inversion point, where there is no heat exchange between the gas and the formation. There, obviously, the temperature T of the gas should equal that of the formation T'; in other words, at the point I, the temperature log crosses the geothermal gradient. This inversion point should correspond to a maximum of the temperature curve. Above I, the temperature in the borehole decreases as the depth decreases, until an asymptotic line is reached. The asymptotic line is parallel to the geothermal gradient.

2. The asymptotic line may be found by going up the temperature log until it is essentially straight and draw-

*In the conventional conditions of wells filled with mud, the temperature logs are run at a time when the gas is prevented from flowing by the mud column. The distribution of the temperature along the borehole is different in that case from that existing in gas producing wells. The discussion of the present paper, therefore, cannot be extended without change to the case of wells filled with mud.

**In Fig. 2 the curve is represented above a bed such as the upper bed in Fig. 1; the same discussion, of course, would be valid for a bed such as the lower one.

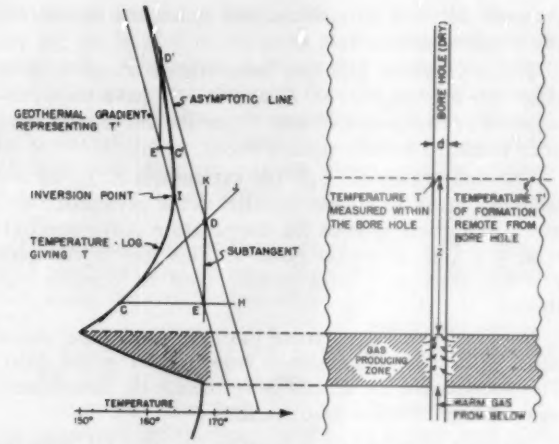


FIG. 2 — TEMPERATURE LOG ABOVE A GAS-PRODUCING ZONE, DETERMINED BY COMPUTATION.

ing a straight line approximating this portion of the log. It is necessary to go far enough above the gas zone to obtain a nearly straight portion of the log — but not too far, however, because the theory assumes that the thermal conductivity of the formation does not change. In practice, the log can be expected to become nearly straight a few hundred feet above the producing zone.

3. The amount of gas produced by a given bed can be derived theoretically from the slope of the curve above the bed. A convenient way for this derivation consists in tracing the *sub-tangent* to the curve. Through any point C on the curve above the producing bed, a tangent CJ and a horizontal line CH can be traced. The vertical line through the intersection at D of the tangent CJ and of the asymptotic line crosses CH in a point E which is located on the geothermal gradient line. The line DE is the sub-tangent to the curve at a point C. The length of the sub-tangent is constant whatever the location of the point C above the producing zone (this is illustrated on Fig. 2 where the sub-tangents DE and $D'E'$ at two different points C and C' are traced).

The length L of the sub-tangent is proportional to the total amount of gas produced by all the beds located below. For practical purposes, a relationship $M = CL$ can be used, where M is the production of gas in thousands of cubic feet per day, at atmospheric pressure, and L is the length of the sub-tangent in feet. The proportionality coefficient C depends on the time elapsed between the beginning of production and the measurements. Its value also depends on the thermal conductivity of the formation, the hole diameter . . . and on the presence or the absence of a casing. The curve of Fig. 3 is a plot of C vs time. The curve was computed for an open hole, 6 in diameter, taking for the thermal conductivity of the formation a value of .0041 cal./degree cm*. This curve can be used, as a first approximation, for the analysis of the temperature logs.

APPLICATION OF TEMPERATURE CURVES — FIELD EXAMPLES

The application of the temperature curves will be discussed on field examples, coming from the San Juan Basin, N. Mex.

*This is the value of K for freshly cut sandstone as given in the Smithsonian Physical Tables, 8th Revised Edition, page 275.

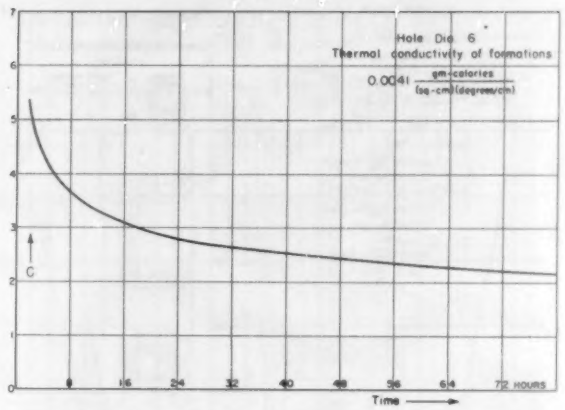


FIG. 3 — PLOT OF C VS TIME IN THE GAS PRODUCTION FORMULA $M = CL$.

M — gas production in thousands of cubic feet per day at atmospheric pressure.
L — sub-tangent in the temperature log measured in feet.

The wells in that region are drilled with water base mud until the top of the gas producing series is reached. The conventional electrical log and the MicroLog then are run and the casing is set. Next, the wells are drilled deeper with dry gas. The temperature log, radioactivity logs, the Induction Log, and eventually the Section Gauge log are recorded while the gas is flowing from the formations. While in the initial period of exploitation most of the wells were shot with nitroglycerine, this procedure is being replaced more and more frequently with hydraulic fracturing.

The producing series includes two main reservoirs referred to in the following as A and B. Reservoir A is usually indicated by the radioactivity and Induction Logs. Reservoir B (the lower one), does not always appear as clearly on the logs. The porosities of the reservoir formations are shown by core analysis to vary between 10 and 15 per cent, the permeabilities are very low — around 1 md.

EXAMPLE 1

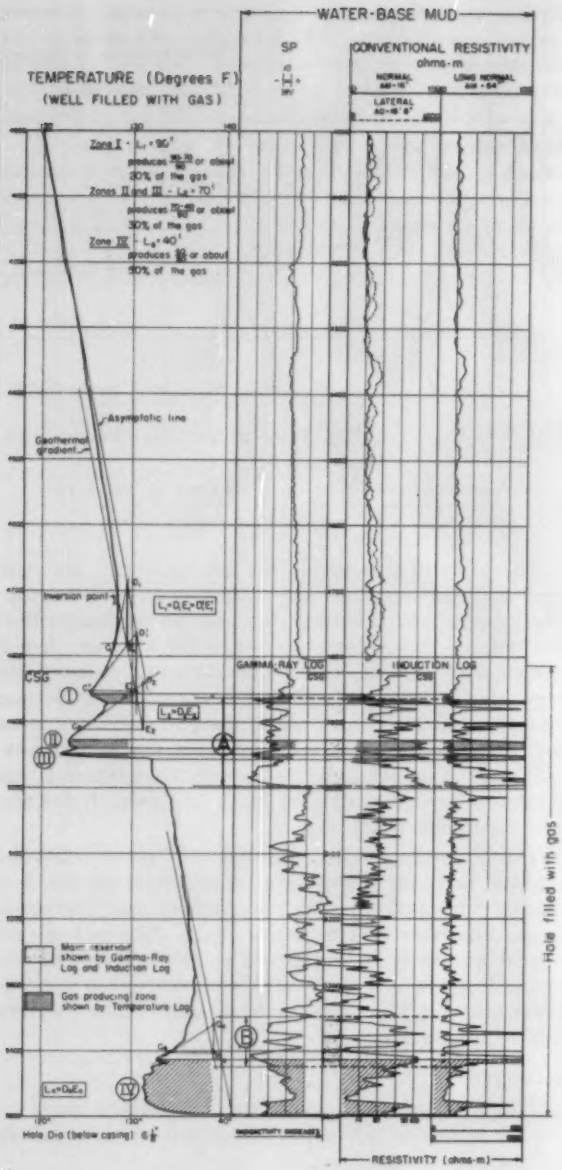
The left-hand track shows the temperature curve recorded in the well while flowing gas and before hydraulic fracturing.

The conventional resistivity curves and the SP curve recorded in water base mud prior to running the casing are traced in the upper right-hand portion of the drawing.

The Gamma Ray Log and the Induction Log, run in the hole filled with gas, are represented at the bottom part. Two Induction Logging curves are traced, which are the reproductions of the same measurements with a hyperbolic and a linear resistivity scale**, respectively.

The part of the well where these two logs were run corresponds to the producing series. The formations are a sequence of sandstones and shales interbedded. Over sections A and B, the proportion of sandstones is greater than in the other portions of the well (the average radioactivity is lower). The resistivities of the sandstones observed on the Induction Log are comparatively high, which suggests the presence of gas. Sections A and B correspond approximately to the two main reservoirs.

**In fact, the Induction Log is primarily a "conductivity log" recorded with a linear conductivity scale, counted from the right to the left. This conductivity scale, when numbered in terms of resistivity, gives the hyperbolic resistivity scale. The curve with the linear resistivity scale is the reciprocal of the conductivity curve.



EXAMPLE 1 — TEMPERATURE SURVEY IN GAS-PRODUCING WELL BEFORE FRACTURING, SAN JUAN BASIN, N. MEX., 1953.

Four main cooling effects, corresponding to four gas producing zones, numbered I to IV are observed on the temperature log.

Zone IV is the closest to the bottom of the hole. If the minor fluctuations are neglected, the curve opposite this section has roughly the shape of a plateau, as described in the theoretical analysis illustrated in Fig. 1. Zones I and III show the characteristic shape defined in Fig. 1 for beds overlying other gas producing zones. Zone II is a very short distance above zone III, and accordingly does not give rise to a large relative deflection.

The comparison of the temperature, the gamma ray, and the Induction Logs shows that zone I straddles the top boundary of section A and includes a part of the overlying shales. Zone II apparently is a shaly sandstone, zone III a sandstone, both located within section A. Zone IV is mostly shaly, and is located almost entirely below section B.

The asymptotic line has been traced above zone I. Also two sub-tangents $D_1 E_1$ and $D'_1 E'_1$ have been constructed at two points C_1 and C'_1 of the curve, and have been found to be substantially equal.

The line drawn through the extremities $E_1 E'_1$ of the sub-tangents is, of course, parallel to the asymptotic line and furthermore crosses the temperature curve approximately at the inversion point I. This line is the geothermal gradient. These results tend to confirm the theory.

It is not possible to trace the asymptotic line above zone II, because the distance from I to II is too short. The sub-tangent $D_2 E_2$ can nevertheless be determined, using the geothermal gradient line.

No such construction is possible for zone III, because the portion of curve between III and II is so short that a tangent cannot be well defined.

An asymptotic line, and a sub-tangent $D_4 E_4$ are also traced for zone IV.

The respective lengths L_1, L_2, L_4 of the sub-tangents opposite zones I, II and IV are 90 ft, 70 ft and 40 ft.

The proportions of the total production contributed by each zone are therefore:

Zone I $\quad \frac{90\text{-}70}{90}$ or about 20 per cent

Zones II and III $\quad \frac{70\text{-}40}{90}$ or about 30 per cent

Zone IV $\quad \frac{40}{90}$ or about 50 per cent.

Taking for the C coefficient a value of 3.5, which corresponds to about eight hours elapsed between the beginning of the production and the time of the logging operation (see Fig. 3), the total production of the well is found to be equal to $3.5 \times 90 = 280$ Mcf/D.

This figure can be compared to the value of 412 Mcf/D measured at the well. The difference is reasonably small, if one considers the various sources of error inherent in the computation (in particular the value of C is obtained from a curve computed for open hole, whereas the well above zone I is cased. Perhaps also, the measurement of the amount of gas produced is not entirely accurate either.)

EXAMPLE 2

In the present instance, after setting the casing the well was drilled with gas to 4,962 ft and a first temperature log was recorded down to the bottom (solid line on the drawing). A first cooling effect can be observed below the casing (zone I), and another one at some distance below (zone II)*. Following this survey, this section was fractured with 10,000 gal of oil and 10,000 lb of sand. The measured production increased from 300 Mcf to 1,850 Mcf/D.

After fracturing, the well was deepened to 5,479 ft and a second temperature survey was made. This second temperature survey shows the effect of hydraulic fracturing in the section from casing to 4,962 ft (dotted line). The lower section, from 4,962 ft to bottom had not been fractured at the time of the second survey (line in dash-dots).

*Zone II is very thin, which explains why the curve does not show a sizeable plateau.

The cool anomalies observed on the second temperature log are located in the same places as zones I and II respectively. The curves opposite and above zone II are little different, which indicates that the production from this zone has not changed appreciably. On the contrary, the slopes of the two curves above zone I are markedly different, and their comparison shows that the production from zone I has considerably increased after fracturing.

The comparative productions of zone I before and after treatment can be roughly estimated in the present case, using the construction of the sub-tangents DE and $D'E$.

The ratio $D'E/DE$ = 300 ft/65 ft = 4.5, compared to 1,850/300 or about 6, as measured.

It can be said also that, if C is again taken to be 3.5, the respective productions calculated before and after fracturing would be equal to 230 Mcf and 1,000 Mcf/D, against 300 and 1,850 measured.

It is furthermore noticed that the amplitude of the cooling anomaly at the level of zone I is much smaller after fracturing than before. An explanation can be tentatively suggested for this somewhat surprising effect: after the process of fracturing, the permeability of the formation, on the average, becomes large around the borehole; beyond this the formation is not affected and the permeability remains small. Accordingly, when the gas is flowing, the radial pressure gradient is comparatively small near the borehole and becomes great only where the formation is untouched. In other words, the greatest part of the cooling occurs far enough from the borehole that the temperature in the borehole is comparatively little influenced.

Example 3

A first temperature survey was made in this well down to the bottom at 5,475 ft before fracturing. One main cooling effect (zone I) is shown, at the level of a sandstone within reservoir A. The second temperature curve, recorded after fracturing, shows this productive zone widely extended upward, throughout the top part of reservoir A and the overlying shaly interval (zone I′).

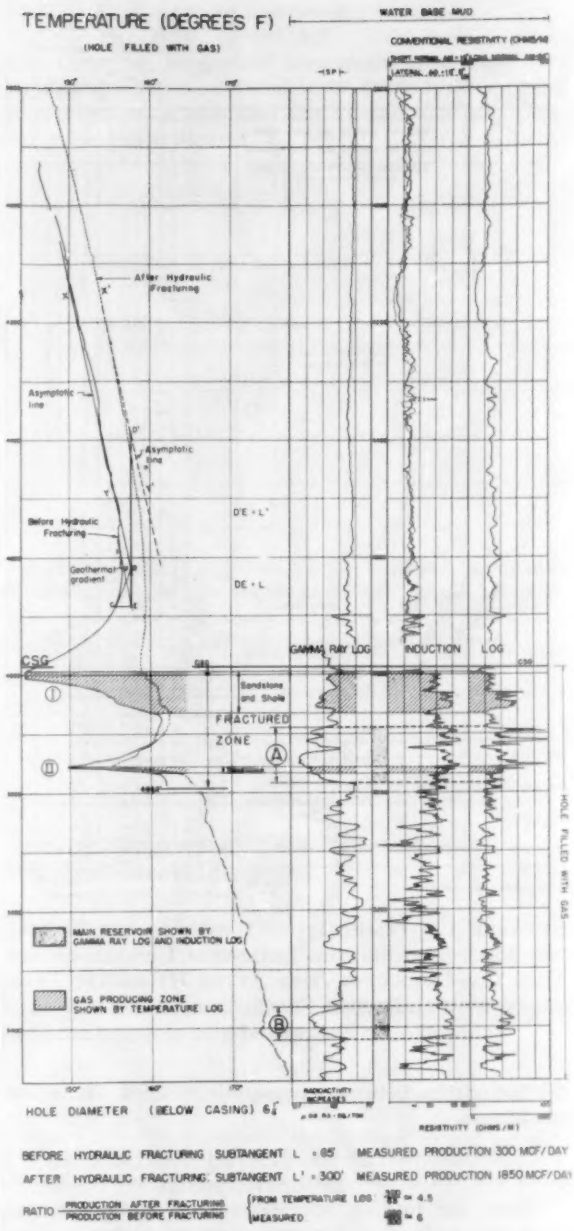
The comparison of the slopes of the two curves, above zones I and I′ respectively, brings to the light the important increase of production after treatment. No subtangents are traced for comparison in the present example, because the curve after fracturing was not recorded high enough to make possible the construction of an asymptotic line.

The log also shows several other zones, which produce small amounts of gas (sharp breaks in the curve): Zone II and zone II′ are sandstones. Zone III′ is a shale, zone IV′ is at the boundary of a shale and a sandstone, and zone V′ includes both sandstones and shales.

Example 4

This survey was also made under conditions identical to the ones described in the preceding examples. The first temperature log shows two gas producing sandstones I and II, within reservoir A. After fracturing, the second curve shows a large cooling anomaly at I′, just below the casing. (Actually, the upper boundary of the gas producing zone is the casing shoe itself.) A comparatively small deflection of the curve is still observed in the vicinity of beds I and II.

The curves, therefore, show that the bulk of the production after fracturing comes from a new zone I′,


TEMPERATURE (DEGREES F)
WATER BASE MUD
(HOLE FILLED WITH GAS)
CONVENTIONAL RESISTIVITY
After Hydraulic Fracturing
Asymptotic line
Before Hydraulic Fracturing
Geothermal gradient
DE = L'
DE = L
CSG
GAMMA RAY LOG
INDUCTION LOG
Sandstone and Shale
FRACTURED ZONE
MAIN RESERVOIR SHOWN BY GAMMA RAY LOG AND INDUCTION LOG
GAS PRODUCING ZONE SHOWN BY TEMPERATURE LOG
HOLE FILLED WITH GAS
HOLE DIAMETER (BELOW CASING) 6¼"
RESISTIVITY (OHMS / M)
BEFORE HYDRAULIC FRACTURING SUBTANGENT L = 65' MEASURED PRODUCTION 300 MCF/DAY
AFTER HYDRAULIC FRACTURING: SUBTANGENT L' = 300' MEASURED PRODUCTION 1850 MCF/DAY
RATIO PRODUCTION AFTER FRACTURING / PRODUCTION BEFORE FRACTURING
FROM TEMPERATURE LOG
MEASURED

Example 2 — Temperature Surveys in Gas-Producing Wells Before and After Hydraulic Fracturing, San Juan Basin, N. Mex., 1954.

which was not producing before fracturing. This zone is located within a shaly interval at some distance above the main reservoir.

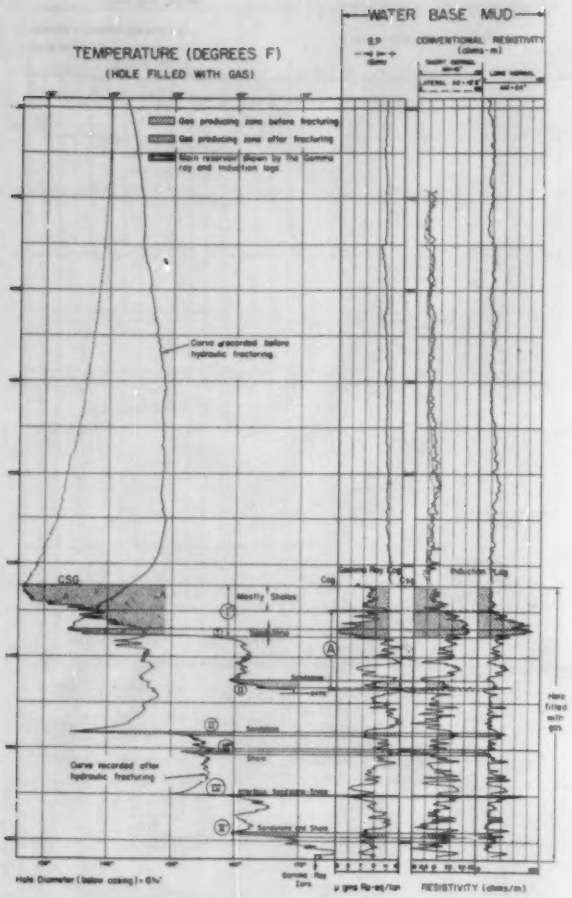
Discussion

Observations

The observations made on the logs and illustrated by the above typical examples can be summarized as follows:

1. The production of gas may come from intervals different from the main reservoir rocks, and this particularly after hydraulic fracturing.

2. The gas producing intervals are often located within those zones where shales are predominant, or near



EXAMPLE 3 — TEMPERATURE SURVEY IN GAS-PRODUCING WELL SHOWING THE EXTENSION UPWARD OF THE MAIN GAS-PRODUCING ZONE AFTER HYDRAULIC FRACTURING (I, BEFORE FRACTURING — I′, AFTER FRACTURING).

the boundaries between comparatively thick shales and sandstones.

3. The gas producing zones after fracturing very often are not at the same depths as before treatment.

When the logging operations were started in this basin, the wells were not yet treated by hydraulic fracturing, and the observation that the gas would escape preferentially across the shaly sections seemed rather surprising. Later on, this tendency has become more conspicuous and systematic in the wells surveyed after fracturing.

It has been, therefore, tentatively concluded that the gas may be produced from secondary reservoirs, such as sequences of thin sandstones within shaly intervals, and/or that it may migrate from the main reservoirs along fractures, either natural or induced, connecting those reservoirs with shaly sections.

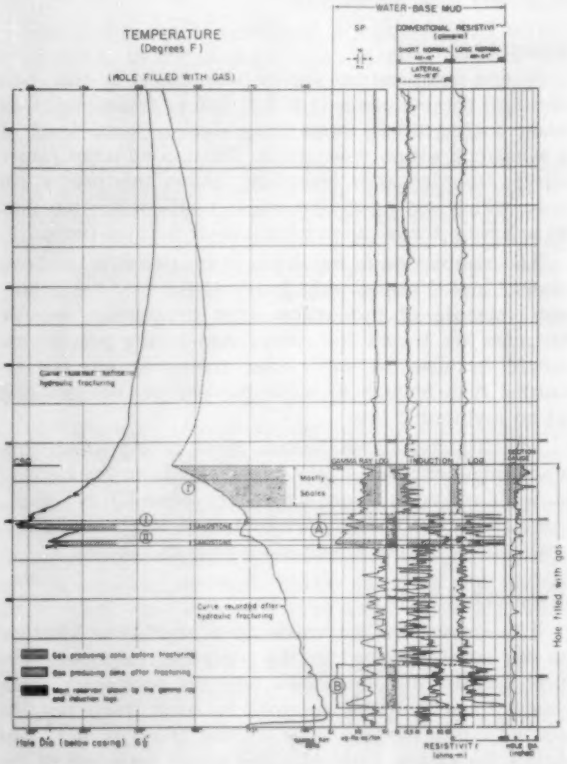
One point of particular interest is that in many instances the temperature logs show the gas coming out from the boundaries between sandstones and shales. Furthermore, those shaly zones which are the main gas producers are actually sequences of numerous thin shales and sandstones. In other words, they contain a large number of sand-shale interfaces, which, in the case of low permeability formations, may constitute the easiest way for the gas to flow into the borehole.

It is likely that the capacity of the interfaces to drain gas does exist in the natural conditions of production. It has been recognized, for example, that section B, before fracturing, usually produces more gas than section A, although the total thickness of reservoir rock is greater in A than in B. This comes from the fact that the beds in section B are on the average thinner and more numerous, and therefore, the interfaces are more frequent than in section A. This capacity of the interfaces is appreciably increased by the hydraulic fracturing, since apparently the interfaces constitute zones of least resistance.

It may be suggested, therefore, that the hydraulic fracturing in general, when operated throughout a large interval which includes other formations besides the reservoir rocks, may result in creating channels at depths which are not necessarily favorable for the most efficient drainage, as for example sand-shale interfaces located at a great distance from the reservoir rocks. It may thus be possible that the initial production obtained after fracturing, although very important, may not keep up because the fracturing operation has opened only some intervals with comparatively small reserves, whereas the main reservoirs may be essentially unaffected by the treatment.

GRAPHICAL CONSTRUCTION

The graphical construction used to determine L is certainly a convenient way to estimate the amount of



EXAMPLE 4 — TEMPERATURE SURVEYS IN GAS-PRODUCING WELL BEFORE AND AFTER HYDRAULIC FRACTURING SHOWING THE DISPLACEMENT OF THE MAIN PRODUCING ZONE FROM SANDSTONES I AND II TO THE OVERLAYING SHALES I′, SAN JUAN BASIN, N. MEX., 1954.

gas produced by each zone. It should be emphasized, however, that the accuracy of this procedure chiefly relies on the determination of the asymptotic line, which is not always obtained with enough precision. One difficulty in this respect is that the temperature logs usually are not recorded high enough above the upper producing zone.

Should the value of the geothermal gradient for the region under investigation be known, the value of L could be also obtained by tracing the geothermal gradient through the inversion point I. But here again, uncertainty will arise as to the location of the point I because of the small curvature of the log around its maximum.

Furthermore, the value of the coefficient C in formula $M = CL$ involves several factors which are not always sufficiently well defined.

The procedure described above cannot, therefore, be considered as applicable in all cases for a determination of the absolute production. It may nevertheless be valuable in assessing the relative productions of each of the zones producing at the same time, or to compare the productions before and after fracturing.

THEORETICAL DERIVATIONS

As stated above, the essential rules for the interpretation of the temperature log have been determined by mathematical analysis and confirmed by field experience. The essential derivations are explained below.

Basic Computations

Let z be the distance measured upward along the axis of the borehole from some convenient reference point, and $M(z)$ be the amount of gas flowing per unit time along the borehole. If $m(z)$ is the amount of gas produced per unit height and per unit time, then clearly

$$\frac{d\,M(z)}{dz} = m(z) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The following assumptions will be made:

1. There is sufficient turbulence in the flow of gas in the borehole that it is essentially homogeneous in temperature and pressure across any section of the borehole.

2. The gas is at the same temperature as the wall of the borehole.

3. Due to its expansion, the gas being produced has been cooled a certain amount δT below the temperature $T'(z)$ of the formation remote from the borehole. This amount, of course, will depend on the nature of the bed. Any effect on the cooling caused by changes in the borehole gas temperature T should be small and is neglected.

4. The effect of heat conduction in the formation parallel to the borehole may be ignored.

5. The pressure in the borehole is effectively atmospheric pressure.

6. Convection of heat in the formation may be neglected.

Consider a small length Δz of the borehole lying between z and $z + \Delta z$. The amount of gas entering this volume from below at a temperature $T(z)$ is $M(z)$ and the amount entering from the formation at a temperature $T'(z) - \delta T$ is $m(z)\,\Delta z$: see assumption 3. These two streams of gas are mixed together and leave the top of this element of volume at a temperature $T(z + \Delta z)$.

The heat absorbed by the first stream per unit time is

$$M(z)\,C_p\,[T(z + \Delta z) - T(z)] \quad . \quad . \quad . \quad . \quad (2)$$

While that for the second stream is

$$m(z)\,\Delta z\,C_p\,[T(z + \Delta z) - T'(z) + \delta T] \quad . \quad (3)$$

with C_p being the specific heat of the gas at constant pressure. The sum of these heats is assumed supplied by conduction of heat from the formation and is therefore given by the expression

$$(2\pi\,a\,\Delta z)\,K\left(\frac{\partial T}{\partial r}\right)_{r=a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where

K: conductivity of the formation

a: radius of the borehole

$\left(\frac{\partial T}{\partial r}\right)_{r=a}$: radial component of the temperature gradient at the wall of the borehole.

It is convenient to write in place of Equation 4:

$$2\pi a\,\Delta z\,k\,[T'(z) - T(z)] \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where

$$k = K\frac{\left(\frac{\partial T}{\partial r}\right)_{r=a}}{T'(z) - T(z)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

is a proportionality constant which, however, is dependent somewhat on the length of time the well has been flowing.

Equating the sum of the expressions in 2 and 3 to that in 5 and dividing by $C_p\,\Delta z$ one has:

$$M(z)\left[\frac{T(z + \Delta z) - T(z)}{\Delta z}\right] + m(z)\,[T(z + \Delta z) - T'(z) + \delta T] = \frac{2\pi ak}{C_p}[T'(z) - T(z)]$$

Letting Δz approach zero and rearranging terms, we have the differential equation:

$$M(z)\frac{dT}{dz} + \left[m(z) + \frac{2\pi ak}{C_p}\right][T(z) - T'(z)] = -m\delta T \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Since the temperature of the formation $T'(z)$ remote from the borehole may be assumed to be given by:

$$T'(z) = T'_o - \frac{z}{g} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where T'_o is the formation temperature at $z = 0$ and g is the geothermal gradient, one may write in place of Equation 7 the differential equation:

$$M(z)\frac{d}{dz}[T'(z) - T(z)] + \left[m(z) + \frac{2\pi ak}{C_p}\right][T'(z) - T(z)] = m\delta T - \frac{M}{g} \quad . \quad . \quad (9)$$

Characteristics of the Curve at the Level of the Gas Producing Zones

Assuming a uniform gas producing bed, $m(z)$ is a constant, which will be referred to as m, and if we take $z = 0$ at the bottom of the bed

$$M(z) = M_o + mz \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where M_o is the quantity of gas coming from the beds below. The differential Equation 9 thus becomes

$$(z + e_o)\frac{d}{dz}[T'(z) - T(z)] + a[T'(z) - T(z)] = \delta T - \frac{1}{g}(z + e_o) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where

$$e_o = \frac{M_o}{m}$$

$$\alpha = 1 + \frac{2\pi ak}{m\,C_p} = 1 + \frac{C}{m} \quad . \quad . \quad . \quad . \quad (12)$$

A general solution of Equation 11 is seen to be:

$$T'(z) - T(z) = \frac{\delta T}{\alpha} - \frac{z + e_o}{g\,(1 + \alpha)} - \frac{B}{(z + e_o)^\alpha} . \quad (13)$$

where B is an arbitrary constant. Assuming that the bed is sufficiently thin so that the change in $T'(z)$ across it can be neglected (this amounts to taking $\frac{1}{g} = 0$), one has:

$$T(z) = T'_o - \frac{\delta T}{\alpha} + \frac{B}{(z + e_o)^\alpha} \quad . \quad . \quad . \quad (14)$$

Solving for B in term of the temperature T_o at the bottom of bed, one then has:

$$T(z) = T'_o - \frac{\delta T}{\alpha} + \left(\frac{z}{e_o} + 1\right)^{-\alpha} \left[T_o - T'_o + \frac{\delta T}{\alpha}\right] . \quad . \quad . \quad (15)$$

When the producing zone is the closest to the bottom of the hole, there is no gas coming from below the bottom boundary; then $e_o = 0$ and in Equation 15 $\left(\frac{z}{e_o} + 1\right)^{-\alpha}$ is also equal to zero.

Equation 15 reduces to:

$$T(z) = T'_o + \frac{\delta T}{\alpha} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

which shows that, if the producing formation is homogeneous, $T(z)$ is constant: in other words, the curve should exhibit a plateau.

For the bed above the bottom beds e_o is no longer equal to zero, and Equations 14 and 15 show that the temperature decreases as z increases.

At the top of a gas producing bed, whether it be the bottom bed or not, the entry of the cool gas from the formation ceases and one has left only the warming due to conduction of heat from the formation. Thus the temperature of the gas will start to rise once the top of the bed is passed, and one has a very distinct indication of the upper and lower limits of a gas producing bed.

Temperature Curve Above a Producing Zone

We will now take $z = 0$ at the top of the bed.

Above a gas producing zone, $m(z)$ is zero and $M(z)$ is constant. The differential Equation 9 therefore becomes:

$$\frac{d}{dz}[T'(z) - T(z)] + \frac{2\pi ak}{M\,C_p}[T'(z) - T(z)] = -\frac{1}{g} \quad (17)$$

The general solution of this differential equation is seen to be:

$$T(z) = T'(z) + \frac{L}{g} - Ae^{-\frac{z}{L}} . \quad . \quad . \quad . \quad (18)$$

where A is an arbitrary constant and

$$L = \frac{M\,C_p}{2\pi ak} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

The last term in Equation 18 becomes small as z becomes large and thus T approaches the *asymptotic line* shown in Fig. 2 whose temperature is given by

$$T'(z) + \frac{L}{g} = T'_o - \frac{z - L}{g} \quad . \quad . \quad . \quad . \quad (20)$$

where T'_o is the formation temperature at the depth of the top of the bed.

This line corresponds to a temperature L/g degrees greater than that of the geothermal gradient, T'. As seen from Equations 8 and 20, it represents the same temperature at z as that for the geothermal gradient T' at $z - L$. Thus it may be looked upon as a vertical displacement of L feet of the geothermal gradient in the direction of shallower depth (see Fig. 2).

This displacement L is equal to the sub-tangent DE at any point C of the curve above the producing zone.

It has been explained qualitatively in the section of this paper entitled "Temperature Curve above a Producing Zone" that the temperature log crosses the true geothermal gradient, at the inversion point I, which corresponds to a maximum of the temperature log. This feature can be proved as follows:

The maximum of the temperature log is obtained by differentiating $T(z)$, given by Equation 18, with respect to z and setting this derivative equal to zero. Thus z_I, the value of z at the maximum, is found from the equation:

$$\frac{dT}{dz} = -\frac{1}{g} + \frac{A}{L}e^{-\frac{z}{L}} = 0 \quad . \quad . \quad . \quad . \quad (21)$$

or

$$z_I = -L\,ln\frac{L}{gA} . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

For this value of z from Equations 18 and 20:

$$T(z_I) = T'_o - \frac{z_I}{g} + \frac{L}{g} - Ae^{-\frac{z_I}{L}}$$

which by Equation 21 is

$$T(z_I) = T'_o - \frac{z_I}{g} = T'(z_I) \quad . \quad . \quad . \quad . \quad (23)$$

Thus the gas temperature log crosses the geothermal gradient at this point.

Determination of Amount of Gas Produced

As shown by Equations 12 and 19 the amount of gas produced M is related to the length L of the sub-tangent, obtained as in Fig. 2, by the equation

$$M = CL \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

The magnitude of C is therefore seen to depend on the length of time the well had been flowing before the temperature log was run. This arises from the fact that the temperature gradient about the hole will decrease with time and less heat will be conducted to the gas for the same temperature difference $T' - T$.

According to Equations 6, 19 and 24, the constant C is given by

$$C = \frac{2\pi Ka}{C_p}\left[\frac{\left(\frac{\partial T}{\partial r}\right)_{r=a}}{T'(z) - T(z)}\right] \quad . \quad . \quad . \quad . \quad (25)$$

For the computation of the second factor in Equation 25, we will consider the case where the temperatures T of the borehole and T' of the formation are independent of z.

The temperature $T(r)$ in the formation just outside the borehole should be very nearly logarithmic with r and given by

$$T(r) = T + (T_o - T)\frac{\log\frac{r}{a}}{\log 2} \quad . \quad . \quad . \quad . \quad (26)$$

where T_a is the temperature at $r = 2a$ and T is the temperature at the wall of the borehole. From this equation

$$\left(\frac{\partial T}{\partial r}\right)_{r=a} = \frac{T_a - T}{a \log 2} \quad \ldots \ldots \ldots \quad (27)$$

which substituted in Equation 25 gives:

$$C = \frac{2\pi K}{C_p \log 2} \frac{T_a - T}{T' - T} = 0.0626 \frac{T_a - T}{T' - T} \quad (28)$$

Here we have taken

$K = 0.0041$ calories/degree-cm*

$C_p = 0.593$ calories/degree-gm (methane).

Changing the system of units so that M is measured in thousands of cubic feet per day and L is measured in feet, the expression for C becomes:

$$C = 8.17 \left[\frac{T_a - T}{T' - T}\right] \quad \ldots \ldots \ldots \quad (29)$$

The ratio of temperatures $(T_a - T)/(T' - T)$ as a function of time was obtained numerically by using a finite difference approximation to the heat flow equation. The graph of C vs time as given in Fig. 3 then results.

CONCLUSIONS

A method for the investigation of gas producing wells has been described, which essentially involves the recording of detailed temperature logs by means of a special high speed thermometer, and wherein the radioactivity and Induction Logs constitute the auxiliary documents.

With this method, the temperature logs determine the exact location of the gas producing zones. In favorable cases, they also give an approximate estimation of the amount of gas produced by each separate zone. The other logs give an approximate delineation of the reservoir formations.

The application of the method has shown that the gas producing zones are not always located at the same depths as the main reservoir formations, but rather within shaly intervals, which contain a great number of sand-shale interfaces. This tendency is emphasized after hydraulic fracturing.

It has also been observed that the gas very often does not enter the wells at the same depths before and after hydraulic fracturing.

On the basis of these observations, a tentative conclusion has been reached that the ways opened by hydraulic fracturing are not necessarily at the right place for the most efficient drainage.

A mathematical study has provided the basis for the interpretation of the temperature logs, by determining the characteristic shape and significant features of the temperature curve opposite and above a gas producing zone.

*See first Footnote page 113.

ACKNOWLEDGMENTS

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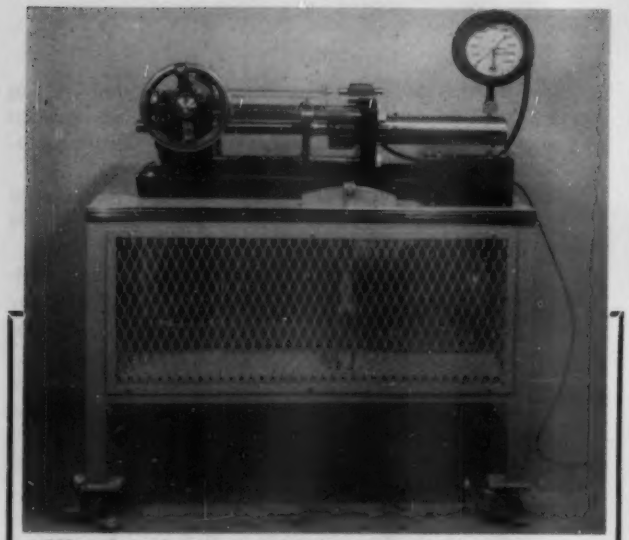

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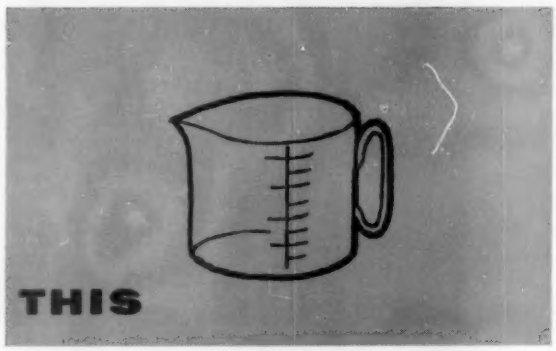

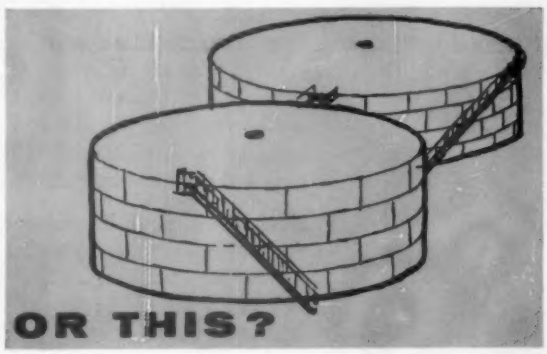

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